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1 A new conceptual methodology for interpretation of mass transport 2 processes from seismic data

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16

17 **Highlights**

- 18 - MTD interpretation is enhanced by a standardized graph-based methodology
- 19 - The proposed methodology integrates the variability of MTD physical processes
- 20 - The methodology is to be shared and improved by the interpretation community

21

22 **Abstract**

23 Identification and seismic mapping of mass-transport deposits (MTDs) are vital targets for marine
24 geological studies both for a better understanding of mass wasting processes and geohazards and for
25 economic prospects in sedimentary basins. In recent decades, refinements in the interpretation of
26 these geobodies have benefited from increasingly good quality 3D seismic data. However,
27 approaches to define the characteristics, rheology and mechanics of such slope failure deposits still
28 rely mainly on inferences from case-dependent interpretations of these stratigraphic elements; what
29 is more, features and seismic characteristics of MTDs may vary significantly from one case to
30 another, implying the existence of many different environments and related physics. This makes the
31 study of submarine mass movement a challenging task for a seismic interpreter. In this paper, we
32 present a new conceptual analytical method based on an objective approach for interpreting the
33 wide range of diverse objects related to mass wasting, in order to minimize seismic interpretation
34 subjectivity. We propose an ontology-like methodology, based on a conceptual organization of a
35 diversity of interpretation elements arranged in a knowledge base. MTDs are considered as objects

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36 with representative properties, each one characterized by several descriptors, which are themselves
37 impacted by multiple physical processes in a graph-based conception. We thus propose a method to
38 infer the most probable interpretations for one mass movement from its deposit characteristics. We
39 applied our graph-based methodology to two MTDs delineated in 3D seismic data in the Offshore
40 Amazon Basin, Brazil. Based on the analysis of all MTD properties and their possible causes, several
41 candidate interpretations were provided. These interpretations yielded by the graph are in line with
42 the known geology and instability processes of the region, thereby validating the feasibility of the
43 approach. The next development stage is a numerical definition of the knowledge base for further
44 sharing and operability.

45 **Keywords**

46 Mass transport deposits

47 Mass transport processes

48 Submarine slope failures

49 Seismic interpretation

50 Knowledge-based interpretation

51 Ontology

52

53 1. Introduction

54 Mass transport deposits (MTDs) are geological bodies resulting from gravity-driven downslope mass
55 movement. As such, they are an invaluable source of information on instability events themselves,
56 and yield insights for current assessment of continental slope geohazards. Submarine slope failures
57 have been shown to contribute significantly to sediment transport and sedimentary records in some
58 basins (e.g. Lee *et al.*, 2007, Shipp *et al.*, 2011). Research on their genesis and evolution should
59 improve stratigraphic analyses on basin infilling and geometries; it may also provide information on
60 their economic petroleum potential and industrial hazard assessment (Alves, 2015).

61 The literature reports that MTD objects can provide direct information on former processes in a
62 basin. Existing classifications of MTDs (e.g., Varnes, 1958; Mulder & Alexander, 2001b; Moscardelli &
63 Wood, 2008; Posamentier & Martinsen, 2011; Talling *et al.*, 2012) illustrate this point correctly, as
64 they tend to relate typical aspects of objects with typical failure-related processes. Classifications are
65 usually based on a combination of internal and external features of the MTD, its depositional
66 environment and the former event itself. Yet case-study interpretations are often site-specific and
67 MTD objects do not always fit in widely validated classification schemes (Vanneste *et al.*, 2014).
68 Similarly, large scale statistics on MTDs (e.g. Owen *et al.*, 2007, Leynaud *et al.*, 2009, Urgeles &
69 Camerlenghi, 2013), although demonstrating links between MTD characteristics and different
70 environments, may not always be applicable in different geological settings. However, a lot of
71 knowledge is unquestionably already available on how to interpret features of MTD objects. The
72 question we tackle here is how to interpret MTD history from their seismic signatures, using available
73 knowledge as objectively as possible.

74 1.1. MTD characterization

75 Given the great complexity and variety of MTDs, their characterization may be a challenging task. In
76 any case, MTD characterization from seismic data starts by a description of the geobody concerned.
77 In such a description, it is important: (1) to include all relevant descriptive features; and (2) to use the
78 information contained in the seismic data as much as possible. The wide variety of these features has
79 been highlighted in the literature. They include: (i) geomorphologic features (e.g. Moscardelli &
80 Wood, 2008), such as general shape and deposit geometry, spatial arrangement/continuity,
81 recognizable 'tongues' showing deposit irregular extension, and a potentially visible headscarp,
82 making it possible to relate MTDs to their original stratigraphic position and loci if not already known
83 (e.g. Vanneste *et al.*, 2014); (ii) kinematic indicators (Bull *et al.*, 2009), such as evidence for flow
84 direction, deformation and/or erosional markers and signs of compression/extension; (iii)

85 stratigraphic elements, such as their position in the depositional succession for timing precision and
86 any attempt to date the deposit. Internal features of MTDs are also valuable to infer event-related
87 processes. Yet the internal architecture of MTDs, and their lateral facies variability, are not often
88 taken into account (e.g. Ortiz-Karpf *et al.*, 2016). 3D seismic data may provide useful information in
89 this respect (e.g. Frey-Martínez, 2010). Thanks to their higher resolution and two horizontal
90 directions, 3D data enable refined and more reliable quantitative characterization of the properties
91 of the object, although extra working time may be required for analysis compared with studies using
92 2D data. Spatial distribution of several MTDs in a basin also proves useful to assess the frequency of
93 slope failure (e.g. Urgeles & Camerlenghi, 2013), as well as the evolution of certain processes in
94 space or over time (e.g., Wu *et al.*, 2011, Ortiz-Karpf *et al.*, 2016, Reis *et al.*, 2016) when ages are
95 constrained.

96 In such a context, previous studies tend to highlight only certain kinds of MTD features depending on
97 the study. But to obtain a complete, objective description of an MTD, all its features need to be taken
98 into account.

99 **1.2. Interpreting MTD processes**

100 From observed MTD seismic features, the processes related to physical failure suspected to play a
101 role in the genesis of an MTD cannot always be quantitatively estimated. Thus, over-simplified
102 interpretations based on descriptive approaches may come out (Vanneste *et al.*, 2014), whereas
103 factual, verifiable relationships are required. In particular, an interpreter should take care when
104 inferring local or too precise conclusions on slope-failure-related processes from statistical or
105 conceptual relationships only. For instance, Urlaub *et al.* (2013) emphasize that the claimed link
106 between sea-level change and mass movement triggering (and therefore the presence of MTD in a
107 sedimentary unit) cannot be statistically inferred from worldwide MTDs – which does not mean it
108 does not exist. Focusing rather on intermediate impacts (e.g. the impact of sea level fall on fluid
109 migrations within the slope basement), which in turn affect slope stability, may make it possible to fit
110 distinct responses of various environments. Unlike over-simplified interpretations, too precise ones
111 may result in interpretations that are ‘overfitted’ to the seismic data. A balance thus needs to be
112 found in the way the interpretation is made.

113 A failure event can be described by its triggering phase (possibly involving pre-conditioning
114 environmental factors), its transport phase and its deposition phase (to which post-deposition
115 processes may be added). The final (present-day) configuration of an MTD typically results from a
116 variety of mass transport-related processes. One event may be generated by several causal processes
117 (Richardson *et al.*, 2011), encompassing both the actual triggering factor and pre-conditioning

118 factors. Identifying one as the only triggering process is incorrect, as they may be mixed and interfere
119 with each other both at temporal and spatial scales. The same is true for mass transport during the
120 event: transport takes place at different scales (e.g. grain scale / flow scale); it involves several
121 physical processes that are linked, even though modeling techniques tend to deal with one process
122 at a time. Therefore, attempts to infer mass transport processes from MTDs should take into account
123 the possibility of multiple influences, and also envisage the possibility of multiple interpretations
124 before selecting the most probable one(s).

125 In all steps of an MTD characterization study (from the initial description to inferring mass transport
126 processes), equivalently encompassing various kinds of processes and MTD features would increase
127 the reliability of MTD interpretation. It would also enable objective comparisons. The principle of
128 MTD classifications tends to oversimplify the description and characterization of MTD features and
129 their causal mass transport processes. To date, the variety of physical processes involved in a mass
130 movement, and the many seismic characteristics of their deposits, have not yet been integrated in
131 non-oriented/agnostic seismic interpretation schemes. Such a scheme should take advantage of both
132 existing knowledge (e.g. the literature) and seismic data specific to a case study, as two
133 complementary sources of information.

134 **1.3. Ontologies for inference problems in geological interpretations**

135 Problems involving multiple data features of different kinds (e.g. quantitative and qualitative),
136 multiple causal factors, and heterogeneous information sources, can be tackled by ontologies (e.g.,
137 Reitsma *et al.*, 2009). An ontology of a domain is an “explicit formal specification of the terms in the
138 domain and relations among them” (Gruber, 1993). An ontology describes the domain exhaustively
139 as a dictionary; it can be used as an inference engine with an adequate method to extract
140 information from it. In geoscience for example, it can link several kinds of data and models, as done
141 by Wang *et al.* (2018) who proposed an ontology on the ‘local geologic time scale of North America,
142 paleontology, and fundamental geology’, together with a method to retrieve information from it. It
143 can also convey the heuristic rules of inference of a domain; for instance, Verney (2009) presented
144 an ontology for structural interpretation of a seismic cube.

145 Ontologies have methodological advantages. They help formalize and separate data-based and
146 knowledge-based elements. They can be shared and improved as much as anyone wishes. They can
147 be used in several ways. They yield repeatable results, and they can be automatized. An ontology
148 could therefore be a relevant approach to the problem of inferring potential causal processes
149 explaining MTD seismic features.

150 **1.4. Contributions and organization of this paper**

151 In this paper, we build a knowledge base conceived as an ontology, which we consider an unbiased,
152 standardized framework to convey the variety of features characterizing MTDs and their generating
153 processes (section 2). We present a methodology for the interpretation of MTDs using this
154 knowledge base. In this methodology, MTDs are considered as objects with representative
155 properties, each one characterized by several features. These features are impacted by multiple
156 physical processes, and these potential impacts are listed in the knowledge base. Our approach is an
157 attempt to merge published results from a multi-disciplinary 'review', to enable the systematic
158 comparison of several objects, while highlighting a variety of mass transport processes. We present
159 an application of our methodology using 3D seismic data acquired offshore the Amazon River Mouth
160 Basin (or Foz do Amazonas Basin, hereafter 'Amazon Basin'); the case study is presented in section 3,
161 and the application of the methodology is detailed in section 4. The validity of our results is analyzed
162 in section 5, and we discuss the global methodology in section 6. Our results enabled the validation
163 of the methodology while revealing its limitations and possible enhancements.

164 Throughout this article, the event(s) at the origin of one MTD will be called (a) mass movement(s).

165 2. Developing a new methodology for interpreting mass-transport
166 processes from MTDs' seismic signatures

167

168 2.1. A new approach to an ontology

169 The methodology developed here relies on a global hypothesis: MTDs' observed characteristics are
170 related to the processes that generated these objects, directly (one process acting on one observed
171 characteristic) or indirectly (one process acting on another one, in turn affecting an observed
172 characteristic).

173 We therefore have to consider an exhaustive description of MTD objects on the one hand, and an
174 exhaustive description of the physical processes involved in the mass movement on the other hand.
175 More precisely, the physical processes considered are those that act before, during or after the mass
176 movement itself, and that may affect the mass movement; they may also be processes evolving at
177 larger scale, associated with the regional or global environment (hereafter referred to as
178 'environmental controls'). Finally, we need to represent the possible impacts of one phenomenon
179 (process) on an observed characteristic of the MTD, or on another phenomenon.

180 Here, we approach such an exhaustive representation of processes for geological object
181 interpretation using an ontology. In our work, an 'MTD interpretation' ontology is a knowledge base
182 containing information from this field of expertise, in the form of relationships, or laws, between key
183 objects or concepts in the field. It is supposed to be exhaustive. The ontology is itself the set of
184 objects (or concepts) and laws. The laws may be obvious, or heuristically accepted, e.g. 'arc-shaped
185 pressure ridges on a MTD indicate a perpendicular flow direction' (e.g. Bull *et al.*, 2009). They may
186 also be laws proven by numerical or experimental modeling, e.g. 'higher initial potential energy of
187 unstable material yields higher runout distance for this material' (Mangeney-Castelnau *et al.*, 2005).

188 We build up our knowledge base as a graph (also termed relation map in this paper). A graph is a
189 diagram consisting of a set of nodes together with edges joining certain pairs of nodes (Merris, 2001,
190 Bondy & Murty, 2008). This representation shows how several objects / concepts, represented by
191 nodes, are interconnected. It can also be represented in the form of an 'adjacency matrix', whose
192 coefficients correspond to the connection between two nodes. In our case the nodes are physical
193 processes of the mass movement, and are also their signatures termed 'MTD descriptors'. The word
194 'descriptor' is preferred to 'feature' as it conveys the notion of a description of an MTD property.

195 Edges can be either lines (for an undirected relationship) or arrows (for a directed relationship), in
 196 which case they represent the impact of one node on another (Figure 1 (a)).

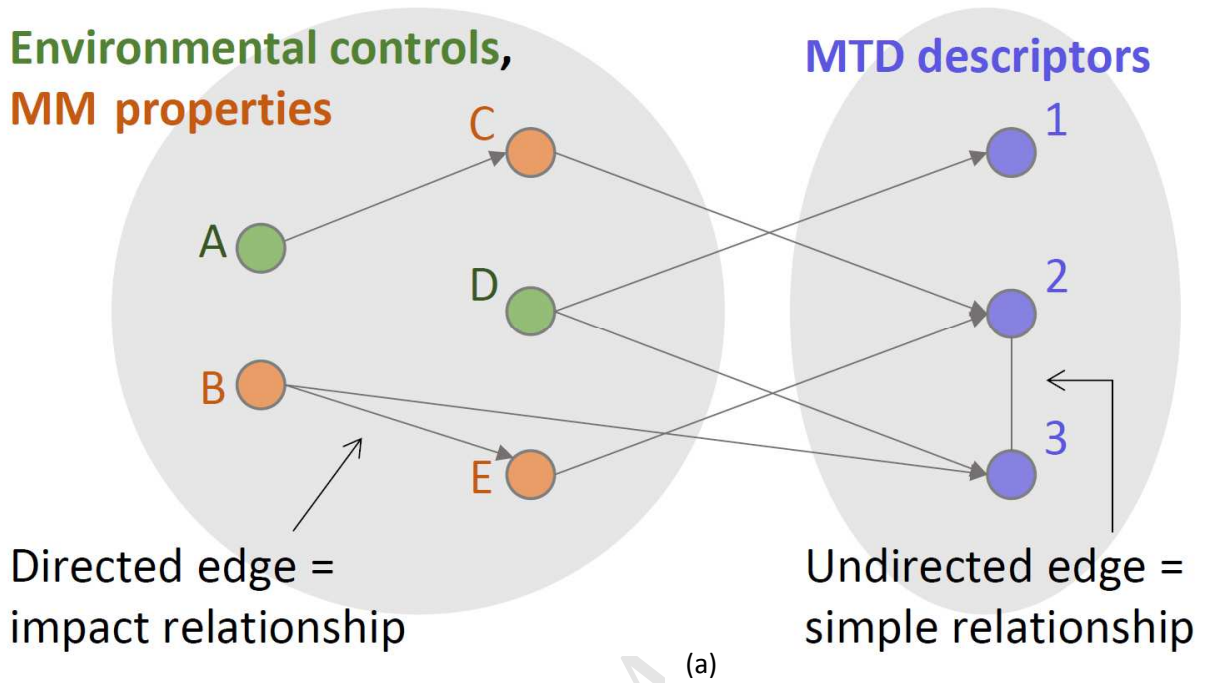


Figure 1. (a) Schematic representation of our graph (relation map). Dots are nodes, colored according to their category (environmental controls, mass movement (MM) properties or mass transport deposit (MTD) descriptors); lines/arrows are undirected/directed edges. Interpretation of MTD descriptor 2 yields nodes C and E as direct potential impacting processes, then nodes A and B; node 3 is only related to node 2. (b) Representation of a sub-part of the global knowledge base, with nodes mentioned in the proposed application (section 4).

202 We only considered works based either on statistical approaches to several well-known MTD cases,
 203 or on conceptual, numerical or experimental modeling (e.g. Mourgues *et al.*, 2014). Case studies
 204 were also used when their results were considered generalizable to other cases (e.g. Sutton &
 205 Mitchum, 2011). Each study considered focuses on one, or a series, of parameters controlling a mass
 206 movement and shows how (to a certain extent) these parameters impact specific MTD descriptors
 207 (e.g. volume, shape of the basal surface, presence of preserved clasts inside the MTD, etc.). We kept
 208 these parameters and the MTD descriptors to use as the nodes. Note that MTD descriptors and
 209 physical processes were filtered to keep only those that are relevant for interpreting seismic data.
 210 The bibliographical selection hopefully suffices to meet the exhaustiveness criterion needed for the
 211 knowledge base – this point could weaken our definition, but the bibliography can be increased
 212 whenever needed.

213 MTD descriptors were gathered into 7 groups (hereafter ‘properties’) that characterize an MTD as a
 214 geological object: Global Environment, Morphology, Position, Basal Surface, Upper Surface, Internal
 215 Facies Distributions, and Headscarp. All the descriptors (listed in the groups in Table 1) are global;
 216 they are either qualitative or quantitative. In the rest of this article, all MTD descriptors are written in
 217 *italics*.

Properties	Morphology	Basal Surface	Upper surface	Position	Head scarp	Internal Facies Distributions	Global Environ ment
Descriptors	thickness variation average thickness width variation horizontal aspect ratio volume surface area maximum horizontal length principal direction presence of ‘tongues’ at toe BS median slope BS flat sub-horizontal zone plunging pool indicator multiple terracing downslope BS ramps	scours, grooves or striations lateral erosive walls BS strong amplitude US median slope US ramps or ridges US with turbidites on top upward connection to other MTDs lateral connection to other MTDs near structural elements laterally runoff distance	HS downslope evolution HS morphology presence of preserved blocks preserved blocks size chaotic facies distribution transparent facies distribution faulty facies distribution ridged facies distribution thrust fault angle increase to toe lithology distribution in MTD deformed facies distribution MTD proportion in sedimentary pile lateral distribution of MTDs vertical distribution of MTDs				

218

Table 1. Characteristic properties of MTDs and their descriptors. BS: Basal Surface, US: Upper Surface, HS: Headscarp.

219 Similarly, we gathered processes in two main groups: external, large-scale environmental controls at
 220 the time of the mass movement (e.g. sea-level curve trend, type of depositional environment,
 221 presence or not of confined topography), and physical properties of the event itself. The latter were
 222 divided into three sub-groups, according to the three phases that describe a mass movement:
 223 trigger-related, transport-related and deposition- (or post-deposition-) related properties. All the
 224 selected environmental controls and mass movement properties are listed in Table 2.

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gravity, short term	Trigger phase	Mass movement properties
seismicity, short term		
fluid overpressure, short term		
offshore events and waves		
chemical effects	Transport phase	
flow velocity and energy		
flow behavior: elastic, plastic, fluid		
local fluidization		
local thickening of flowing material		
volume of transported material		
flow direction		
modifying basin morphology		
inducing seismicity		
triggering turbidity current		
triggering cascading mass movements		
erosion of underlying material		
plunging pool effect		
plowing effect on underlying material		
detached MTD	(Post-) deposition phase	
grains heterogeneity in flowing mass		
fluid overpressure on basal surface		
fluid overpressure in moving mass		
initial potential energy of mass		
lithology in transported mass		
frontal compression		
loss of mass		
remobilization		
compaction during burial		
posterior fluid migrations	Environmental controls	
post deposition regional deformation		
trigger turbidity current at stop		
post deposition of turbidites		
terminal dispersion		
seismicity or waves, long term		
evaporite deformation & mud volcanism		
sea level evolution		
basin depocenter position		
subsidence/uplift, extension/compression		
existing geomorphology, objects and pathways		
sedimentation rate and type		
pore pressure increase by compression		
pore pressure increase by fluid migration		
permeability increase		
lithology of underlying material in source zone		
initial aspect ratio and top of mass slope angle		
topography confinement downwards		
seafloor effective friction angle		
seafloor shapes and dip variations		
source domain in basin		
lithology of underlying material downslope		

Table 2. Environmental controls and mass movement properties. 'Mass movement properties' comprise properties of the trigger phase, the transport phase and the deposition phase (possibly including post-deposition modifications). 'Environmental controls' are large-scale processes.

226 Finally, relationships between nodes were drawn to construct the edges, and were also extracted
227 from the bibliographical study. Here, most of them are directed (arrow), representing the potential
228 impact of one node on another. A directed edge may connect one process and one MTD descriptor,
229 as a direct impact of the former on the latter; or it may connect two processes (two nodes listed in
230 Table 2), thus allowing large-scale/conceptual/statistical controls to have an indirect impact on MTD
231 descriptors through smaller-scale relationships. The list of edges is provided in supplementary
232 material (Table_Supplementary 1).

233 **2.3. Details and analysis of graph content**

234 Here we first provide details on a few nodes (Table 1 and Table 2) and on the graph itself.

235 2.3.1. MTD descriptors nodes

236 In the Morphology property, the descriptor *principal direction* corresponds to the principal
237 orientation of the 3D geobody (in its current state, or inferred at the time of deposition if restoration
238 has been performed). The descriptor *presence of 'tongues' at toe* is a binary indicator of whether
239 some 'fingering' instability occurred at the front of the mass flow (typically triggered by grain size
240 segregation), yielding a non-smooth toe region with 'tongues' (Pouliquen *et al.*, 1997, Woodhouse *et*
241 *al.*, 2012).

242 In the Basal and Upper Surface properties, descriptor *median slope* includes the value of the slope
243 median and its lateral variability over the MTD basal/upper surface, in order to capture typical relief
244 while not taking into account fault- or ramp-induced extreme relief. *Ramps* are stair-like structures
245 on basal or upper surfaces (e.g. Bull *et al.*, 2009). The *plunging pool indicator* is a reversed bell shape
246 on a surface, associated with a hydraulic jump at a slope change in turbiditic systems, or with a
247 unique high-energy mass movement that digs into the underlying sediment (Lee *et al.*, 2002, Bourget
248 *et al.*, 2011).

249 The Headscarp property has two descriptors: *HS downslope evolution* indicates whether a series of
250 headscarps are positioned gradually more basinwards with time (i.e. rising in the sedimentary
251 deposits); *HS morphology* is a qualitative labelling of a headscarp between types 'onlap of upper
252 surface on basal surface', 'cookie-bite', and 'unclear evacuation zone' (Richardson *et al.*, 2011, Dalla
253 Valle *et al.*, 2013).

254 In the Internal Facies Distributions property, all facies distributions are typically described by their
255 internal variations in the 3D space, comparing different regions within the geobody. The *ridged facies*
256 is depicted by overlapping reflectors in the seismic data; whereas descriptor *thrust fault angle*

257 *increase to toe* is a binary indicator for cases with specific initial internal geometry or seafloor slope
258 (Richardson *et al.*, 2011).

259 Note that all descriptors may not be available for all kinds of data/objects observed. In practice, two
260 main limitations may prevent the availability of one or several descriptors: (i) if the MTDs and their
261 corresponding headscarps are not entirely imaged within the seismic dataset used; (ii) if the data
262 resolution is insufficient for Morphology, Facies and Environment precise descriptions, and if the
263 surfaces needed were not picked with sufficient precision. First, to guarantee the detection of the
264 top and bottom surfaces of an MTD, typically two reflectors, its thickness must be more than twice
265 the seismic vertical resolution (ratio thickness/resolution > 2). When characterizing the MTD
266 properties, more constraints apply. Facies descriptions within the MTD require a larger MTD
267 thickness/resolution ratio: ~3 or higher, depending on the kind of facies (~3 for imaging deformed
268 reflectors, ~5 for spotting preserved clasts within a matrix). This is more often the case for MTDs that
269 are not too deeply buried (Alves *et al.*, 2014). Concerning surfaces, slope variations that allow
270 description of ramps, for example, will not be seen if they occur at smaller scales than the precision
271 of the picked surface. Morphological descriptors, as well as specific descriptors of the headscarp, or
272 of the toe, of an MTD, require that these parts of MTDs be covered by the dataset. An estimation of
273 the needed data quality for acquiring each input descriptor is provided in supplementary material
274 (Table_Supplementary 2).

275 2.3.2. Process nodes

276 Processes nodes (Table 2) are not thoroughly detailed here. We here only mention that, in
277 Environmental Controls, 'evaporite deformation' and 'mud volcanism' were combined in one node to
278 account for non-tectonic deformation in general, comprising mud volcanism, creep of evaporites,
279 and even potentially diapiric movement of mud or salt (e.g. Moscardelli & Wood, 2008, Posamentier
280 & Martinsen, 2011, Omosanya & Alves, 2013). The node 'subsidence/uplift, extension/compression'
281 corresponds to large-scale tectonic or isostatic controls. Concerning the node 'plowing effect on
282 underlying material' (*sensu* Posamentier & Martinsen, 2011), it implies reworking the sediments of
283 the underlying stratum with the basal material of the flowing mass, capable of inducing compaction
284 and dense deposition in the basal part of the mass.

285 Finally, there are no nodes for mass movement classes according to existing classifications (see e.g.
286 those mentioned in the Introduction), since mass movement classes may differ from one
287 classification to another, and since they do not correspond to actual processes.

288 2.3.3. Graph analysis

289

290 Taking all nodes and edges together, the final graph built in this work (relation map) counts 88 nodes
291 (38 MTD descriptors and 50 processes) and 173 edges. A full graph visualization is provided in
292 Figure_Supplementary 1 (supplementary material), with a map of nodes and edges, and a
293 representation of the adjacency matrix; this visualization illustrates the variation in the 'degree' (i.e.
294 the number of edges connected to them) between nodes, by node size variation.

295 The 'degree' of the nodes is an analytical tool for graphs in general. Here (as also shown in Figure 1
296 (b)), it is not evenly distributed among nodes. Some processes (with a high 'degree') are therefore
297 more likely to impact final MTD descriptors than others. These are the flow behavior (rather viscous
298 or fluid), geomorphological objects and pathways already present at the mass movement time,
299 sedimentation rate and type at that time, the presence of topographic confinement downwards, and
300 the heterogeneity of the flowing material.

301 From the adjacency matrix of the graph, we highlight that no edge exists between trigger-related
302 processes and MTD descriptors (no connection appears in the corresponding regions of the matrix).
303 The impact of the former on the latter is indirect: trigger properties impact transport-related
304 processes, which in turn impact MTD descriptors.

305 **2.4. Methodology: how to use the graph (relation map)**

306 As an ontology, our knowledge base can be used as an inference engine, i.e. to infer new results on
307 potential causal processes from an applied case study.

308 The MTD interpretation methodology, relying on the graph, is divided into three steps:

- 309 • First, we characterize each MTD by a detailed description of its seven properties: for each
310 property, we give a value to its quantitative/qualitative descriptors. Qualitative values are
311 taken from data observation; quantitative values are obtained from a few computations on
312 the data. Some edges guide the acquisition of descriptors, e.g. the description of 'lateral
313 erosive walls' also includes whether they are seen on only one edge or on more, as this
314 element is impacted by an edge. After this step, the MTD is characterized by 38 descriptors
315 (Table 1) if all are available in the data.
- 316 • Then, for each descriptor, we look for all the edges (arrows) that point at it; possible controls
317 or event properties (among those listed in Table 2) that may have an impact on the
318 descriptor under consideration are given at the other end of these arrows. This corresponds
319 to looking for the possible *causes of/explanations for* the descriptor's value. We note all the

320 possible 'causes' that the graph suggests, no matter how relevant they are with respect to
321 other factors.

322 • Lastly, for each possible 'cause' listed in the previous step, we evaluate how uncertain it is: if
323 the cause was found several times (i.e. if several descriptors pointed to it), then it is quite
324 likely; if another cause was found that contradicts it, then it is highly uncertain, as is the
325 other one. This implies that the *explanation* for some MTD descriptor might remain unsolved
326 until cross-checking with one or several other descriptors. Thus, a result from the graph is
327 obtained only when all available descriptors have been analyzed.

328 The final results of the relation map are not necessarily final interpretations, but rather hypotheses;
329 the relevance of the methodology should be made explicit by the consistency between these
330 hypotheses and available knowledge on the zone.

331

332 **3. Presentation of the Amazon case study**

333 This section presents the geological settings of the region selected to test our methodology: the
334 Amazon Basin. It also presents the data and material we used as inputs when applying the
335 methodology.

336 **3.1. The Amazon Basin and MTDs**

337 The Amazon Basin sedimentation has been highly impacted by gravitational processes, at large and
338 small scales (e.g. Reis *et al.*, 2010, Reis *et al.*, 2016, Silva *et al.*, 2016). Its geological history is closely
339 related to that of the South-American continent. Since the onset of the Amazon River as a
340 transcontinental river, believed to have occurred during the Miocene together with the Andean uplift
341 (11.8 – 6.8 Ma, Figueiredo *et al.*, 2009), the river sediment discharge has kept increasing,
342 progressively building up siliciclastic series on top of an in-place Cenozoic carbonate platform and in
343 the basin. A deep-sea fan has developed farther from the continental shelf.

344 The current Amazon Basin is marked by large-scale gravitational deformation and several huge MTDs,
345 marks of intense destabilization on the margin. These large MTDs have been documented and dated
346 approximately; they are positioned in two zones: NW and SE from the main canyon axis (e.g. Reis *et*
347 *al.*, 2010, Reis *et al.*, 2016, Silva *et al.*, 2016, Figure 2).

348 Smaller-scale MTDs are also visible, on or near the fan; some of them are definitely linked to basin-
349 scale compression-extension processes. Globally though, the origin of these MTDs could be related
350 to channel-levee complex instabilities on the deep-sea fan (Damuth & Embley, 1981), instabilities
351 from fold-and-thrust belts on the deep-sea fan (Reis *et al.*, 2010), sea-level drop inducing gas-hydrate
352 destabilization (Maslin *et al.*, 2005), and/or sediment collapsing under their own weight (Reis *et al.*,
353 2016).

354 **3.2. MTDs in the NW part of the basin**

355 Our study focuses on a sub-basin: the NW region of the basin, where the Amapá Megaslide (AM) has
356 been studied and mapped by Silva *et al.*, 2010, Silva *et al.*, 2016 and Reis *et al.*, 2016 (Figure 2). AM
357 consists of several mass transport complexes (MTCs): (1) The Amapá Lower Complex, (AM1 in Reis *et*
358 *al.*, 2016) is the oldest (late Miocene) and probably results from the collapse of the mixed carbonate-
359 siliciclastic platform; (2) the Amapá Upper Complex (comprising AM2 to AM6 in Reis *et al.*, 2016) is
360 more recent (Pleistocene) and probably results from destabilizations of siliciclastic sediments on the
361 marine slope favored by a regional décollement level – they were indirectly triggered by
362 overpressure on this level on the deep-sea fan. The 50°W and Western MTD (also called Western

363 Debris Flows) are superficial MTDs (Figure 2), uncertainly dated 15 to 75 ka (Damuth & Embley, 1981,
 364 Damuth *et al.*, 1988). Both are associated with the deep-sea fan development and instabilities in the
 365 rapidly accumulated sediments on the fan flanks (Maslin *et al.*, 2005, Damuth & Embley, 1981).

366 In this paper, we analyze five MTDs observed in the basin of this NW region (see following section
 367 and Figure 3). Their lateral position covered by our seismic data (dark orange in Figure 2) is a few
 368 tens of km away from the sides of the Amapá Upper Complex and 50°W MTD.

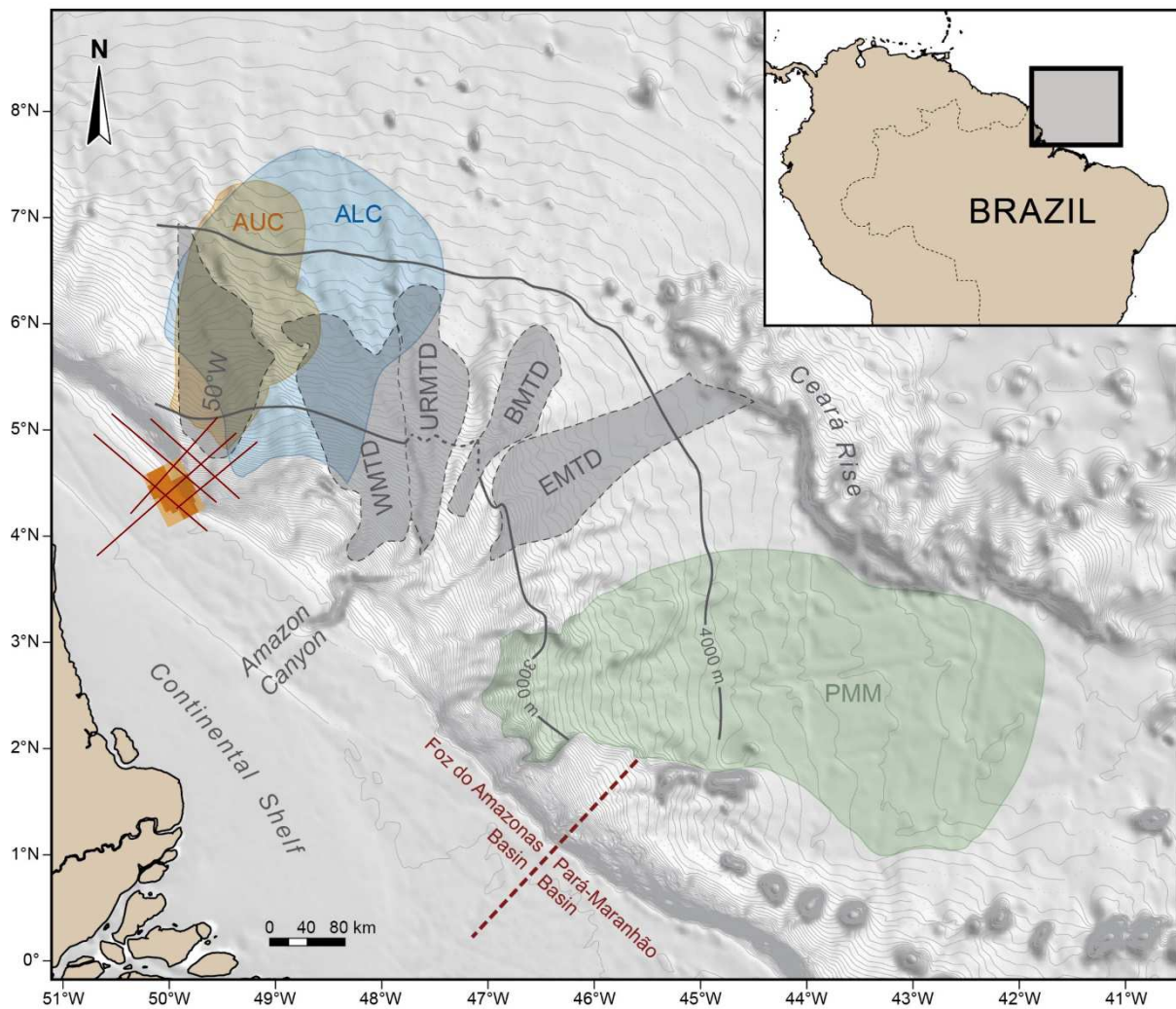


Figure 2. Bathymetric map of the Offshore Amazon Basin with the location of major previously-studied MTDs and seismic data used in this article. Modified from Reis *et al.*, 2016 and Silva *et al.*, 2016. The 50°W (Damuth & Embley, 1981), WMTD, EMTD (Western / Eastern MTDs, Damuth *et al.*, 1988) are superficial MTDs. URMTD and BMTD (Unit R / Buried MTDs, Damuth *et al.*, 1988) are buried. The Amapá and Pará-Maranhão Megaslides (ALC-AUC / PMM) were studied by Silva *et al.*, 2010 and Reis *et al.*, 2016. Amapá Lower Complex (ALC), the deepest mass transport complex of Amapá, is mapped in blue; Amapá Upper Complex (AUC), more recent, is mapped in orange, after Reis *et al.*, 2016. The 3D seismic cube is mapped with available seismic data in dark orange and 2D seismic profiles are mapped in dark red.

370 3.3. Data and materials – input descriptors for the methodology

371 Given the list of seismic MTD descriptors (Table 1), the mandatory data to test our relation map on
372 MTDs in a seismic dataset consist of (i) basal and upper surfaces of each MTD delineated in the
373 seismic data, (ii) position and headscarp descriptors of MTDs (contextual information), and (iii)
374 seismic facies distributions for the seismic data and specifically for each MTD.

375 The seismic data used in this study is a post-stack time-migrated 3D cube granted by CGG Houston.
376 The dominant frequency of the signal is 37 Hz, yielding a vertical resolution of 10 to 20 m
377 (considering velocities from 1500 to 3000 m/s). The cube size is 60 x 43 km (2388 inlines, 1732
378 crosslines), with 25 m of intertrace; in this rectangle, data is only partially available (see dark orange
379 in Figure 2). The cube is on the current shelf break with dip-oriented inlines, at the junction of three
380 major domains: shelf, basin and deep-sea fan in the southern part. Upslope scarps were hand-picked
381 in this cube and interpolated as surfaces using the GOCAD interpretation software.

382 For the MTDs description, a smaller cube was selected, in the deep Amazon Basin setting; it was
383 restricted to a clastic sedimentary succession (2 sTWT thick) lying above the paleo-carbonate
384 platform. The extent of our case study area was therefore 13 x 18 km, counting 512 crosslines and
385 710 inlines (see Figure 3). In this smaller cube, five observed MTDs were selected for analysis here.
386 Their basal and upper surfaces were hand-picked on 72 inlines out of the 710 of the 3D seismic cube,
387 using MATLAB and the GOCAD interpretation software. Figure 3 shows the MTDs, and upslope
388 scarps, within the 3D seismic frame. The MTD thicknesses are ~50 ms in average, minimum 40 ms
389 and maximum ~95 ms. The thickness/resolution ratio is therefore of 3 to 7.1 (for velocity of 1500 to
390 3000 m/s), which ensures the proper acquisition of input descriptors (see section 2.3 and
391 Table_Supplementary 2). Among the five selected MTDs, MTDs A and B, which we analyze in more
392 detail in the following section, are the deepest. They appear to be at the base of a seismic unit
393 overlying a slope sedimentary series (Figure 4).

394 Comparisons of our analytical results with those of published seismic data rely on a few 2D seismic
395 lines with 10-20 m vertical resolution, and a few previously-dated horizon surfaces provided by
396 published material (e.g. Gorini *et al.*, 2014, Reis *et al.*, 2016). The horizons and seismic lines
397 correlating with our seismic block made it possible to assess a stratigraphic constraint in the studied
398 region; upslope scarps and downslope MTDs are all more recent than 2.4Ma.

399 We added our classification of seismic facies to the 3D input data. The classification, which was used
400 as an input for this methodology, was made independently using a method developed by the IFPEN
401 research group. A detailed discussion of the quality of this classification is beyond the scope of this

402 paper, but will be the subject of an upcoming paper. The classification, which resembles that of Roy
403 *et al.* (2014), was applied as follows: (i) the data were clustered into most-similar regions, which led
404 us to associate seismic facies labels to clusters of similar seismic properties; (ii) this procedure
405 enabled us to label each sample of the seismic data with one or several names of seismic facies. Here
406 we use the chaotic, transparent, deformed, strong-amplitude sub-horizontal, and ridged facies. They
407 are detailed in Figure 5. Note that other facies descriptions (e.g. Alves *et al.*, 2014), if associated with
408 seismic facies labels ('chaotic', 'deformed' etc.), could be used equivalently. The associations of facies
409 labels with their descriptions have to be reliable and avoid pitfalls related to acquisition/processing
410 footprints in seismic facies analysis (Marfurt & Alves, 2015). Note that the seismic facies defined in
411 this way are not mutually exclusive, i.e. a region in seismic data may have a 'chaotic' facies and a
412 'transparent' facies at the same time². Such multi-facies samples simply have several labels (e.g.
413 chaotic and transparent) with no prevalence of one over the other.

414 Quantitative descriptors of the Internal Facies Distributions and of the Basal and Upper Surface
415 properties were assessed within the MTDs and on their contours. The proportions of facies within
416 MTDs were calculated, either by summing globally, or along a vertical or lateral direction. This
417 enabled us to obtain maps or lateral variation plots, respectively. Additional information include the
418 proportions of facies integrated over the 3D cube, and basal and upper surface gradient magnitude
419 and direction, initially calculated using the time data and then assessed in °, a more practical unit, for
420 a wave velocity range of [1500 to 3000 m/s].

421

² This is to be kept in mind for the analysis of results in terms of the proportion of facies in MTDs: the addition of the proportion of several facies inside a 3D object is not relevant.

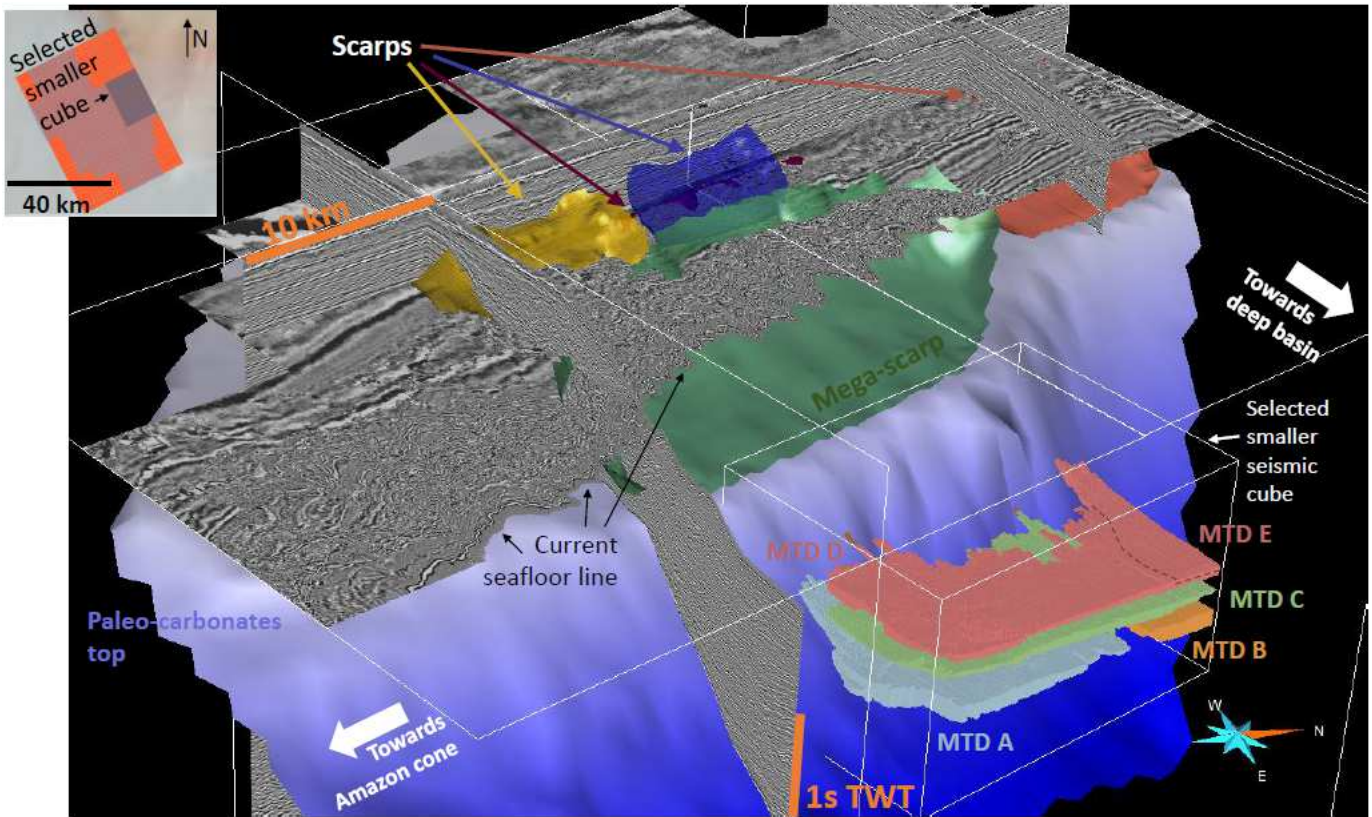


Figure 3. 3D view of the five MTDs highlighted in the studied data. MTDs D and E are separated by the brown dashed line. Colored surfaces are upslope scarps. Grey sections are seismic sections from the seismic cube. The largest blue surface is the top of the carbonate platform (see also Gorini et al., 2014).

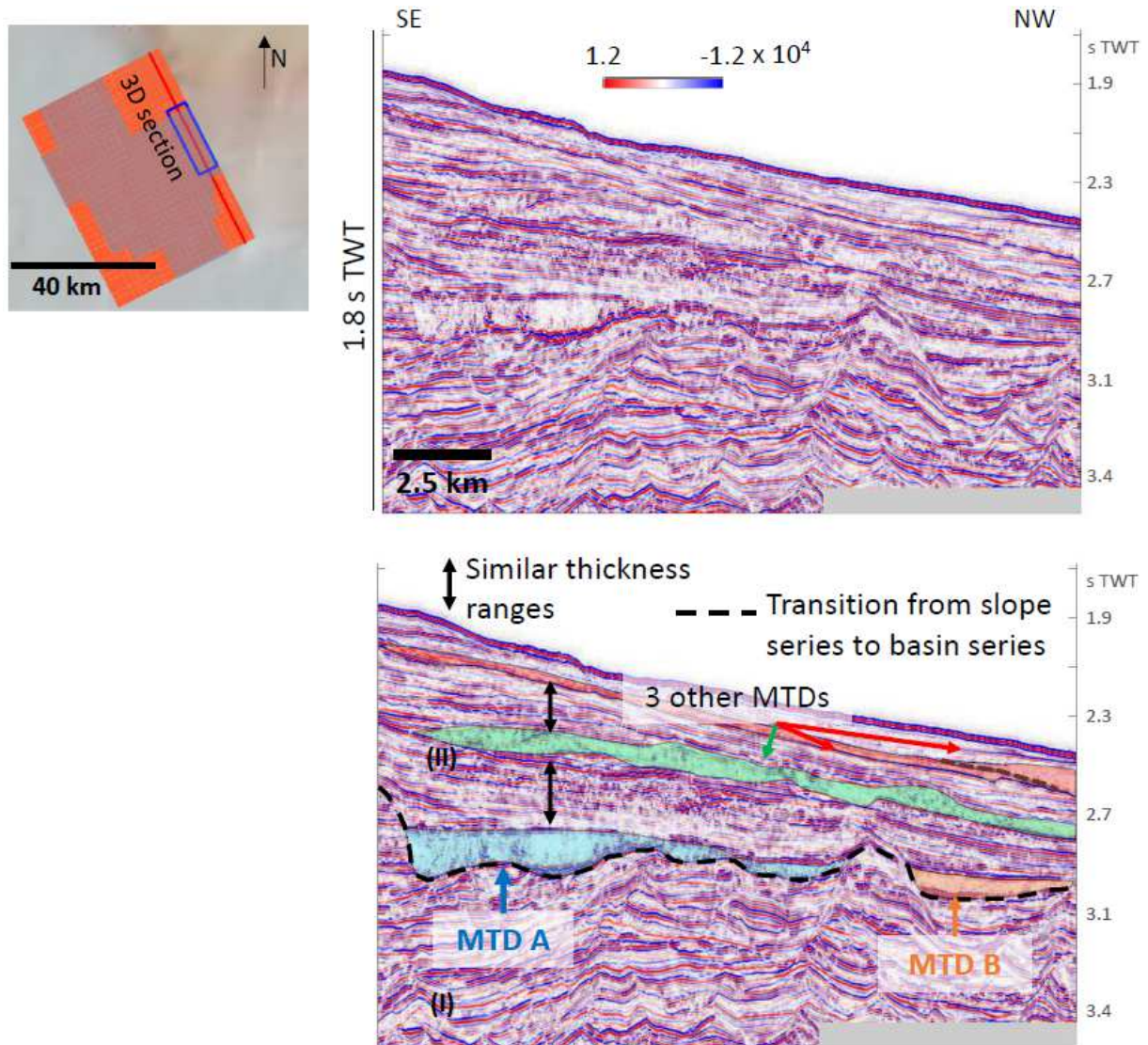


Figure 4. The 5 MTDs highlighted in one seismic section of the post-stack seismic cube (uninterpreted and interpreted seismic sections). MTDs A and B appear to mark the beginning of seismic unit II above seismic unit I. The 3 stratigraphic periods for MTD deposition are separated by roughly similar thicknesses.

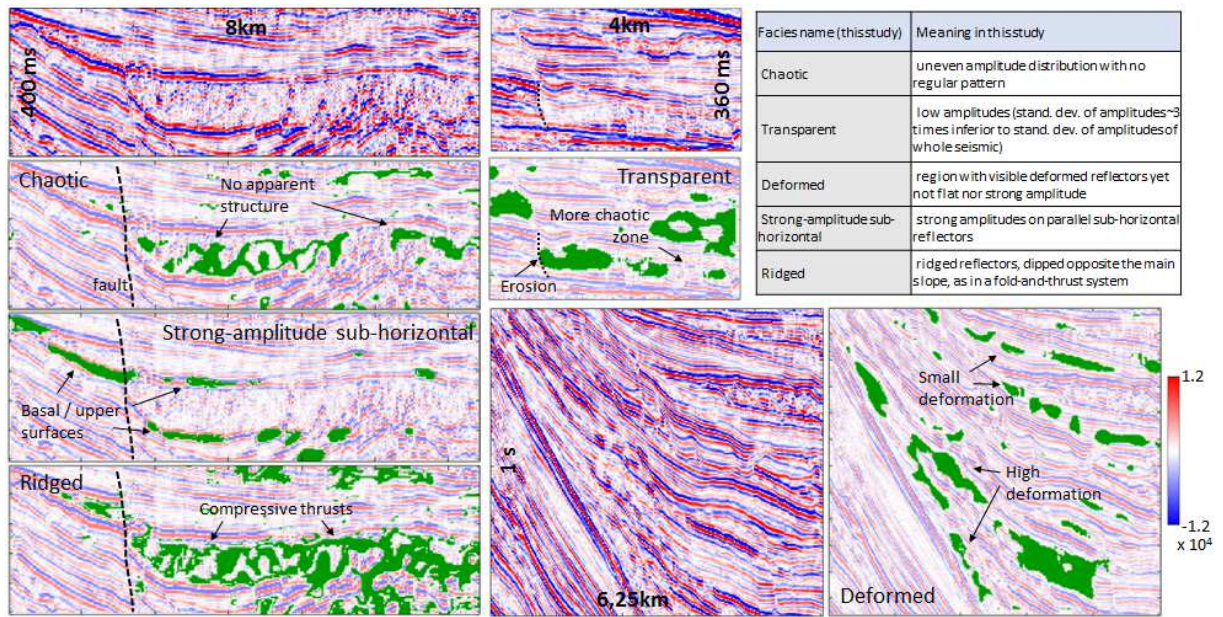


Figure 5. Precise meaning ascribed to each facies used in this study, coupled with examples on seismic sections (shown as green patches on top of the seismic sections). Facies were interpreted based on an automatic method developed by the IFPEN research group, not detailed in this paper.

422

423

4. Application of the methodology to the case study

In this section, we describe how to use the relation map to derive a set of possible interpretations from MTD descriptors. We study the two deepest MTDs: A and B (Figure 3, Figure 4), among the 5 MTDs available and within the cube.

For MTDs A and B, for each of the 7 properties (Table 1) defined in our methodology, we retrieve associated descriptors (among those available in our data for these MTDs) and detail the steps of the methodology. Note that the relation map yields several hypotheses that are not final interpretations; they are possibilities, listed and estimated with the unbiased approach of the ontology – contextual knowledge should then help select most probable hypotheses. Figure 1 (b) illustrates this application with only the nodes mentioned in the text – the full graph is available in Figure_Supplementary 1 (supplementary material).

4.1. Global Environment

The Global Environment property has a few descriptors, which here concern the series of five MTDs (Figure 3). In our small seismic cube, the calculated global *proportion of MTD-delineated sediments* in the recent sedimentary series is 9%.

The *vertical distribution* of our five MTDs shows three main stages of deposition of sedimentary bodies (as two pairs of MTDs are in the same stratigraphic level). Firstly, this *vertical distribution* yields the relative age of all MTDs: MTDs A and B are the oldest. Secondly, the three main stages of sediment disruption are separated by a roughly similar thickness of sediments (Figure 4). According to the relation map, this vertical (almost) cyclical deposition could correspond to sea-level cycles (node 'sea-level evolution' impacting descriptor *vertical distribution*) – if the MTD stages are interbedded with channel-levee systems (Sutton & Mitchum, 2011), which is not obvious from the data only. Alternatively, tectonic- or isostasy-related large-scale deformation could explain this vertical distribution (impact of the node 'subsidence/uplift, extension/compression'). Within the stages with two MTDs, the nodes 'existing geomorphology, objects and pathways' and 'basin depocenter position' may impact the *lateral distribution* of MTDs, showing potential influences of the seafloor shape. The absence of MTD in the south-eastern part of the cube suggests that throughout this period of clastic deposition, the sub-basin depocenter was never located in that part – but instead more basinwards, or more to the north-west; or, that the sub-basin south-eastern geomorphological conditions made it less exposed to mass-transport deposition.

4.2. Morphology

455 Descriptors depicting the property Morphology are now highlighted, with a specific focus on MTDs A
456 and B.

457 The *average thicknesses* of MTDs A and B, 97ms and 90ms respectively, are the largest of all five
458 MTDs identified in the seismic cube. On the relation map, the *average thickness* node is related to
459 the 'volume' node, which in turn is impacted by several nodes concerning transport- and deposition-
460 related processes, such as: 'volume of transported material' (quantity of material), 'loss of mass',
461 'erosion of underlying material', 'compaction during burial', and 'remobilization'. Considering that
462 these MTDs are the oldest ones in the stratigraphic succession studied, they are the most likely ones
463 to have been modified after deposition (by compaction); this suggests that when they were
464 deposited they were even thicker compared to the other MTDs. Moreover, 'loss of mass' during the
465 event itself, or subsequent remobilization, would have decreased the final quantity of deposited
466 material compared to the initially-destabilized mass. As for process 'erosion of underlying material',
467 it could decrease or increase the material quantity depending on the kind of erosion, which is not
468 known for now. Therefore, the initial volume of sediment that was transported to generate MTDs A
469 and B was probably equal to, or greater than, the current MTD volumes.

470 While MTD B is consistently thin on its upper sides and thickens downwards, MTD A has two distinct
471 thicker zones. From the relation map, we know that node *thickness variation* is impacted by the
472 nodes 'remobilization', 'frontal compression', 'local thickening of flowing material', 'terminal
473 dispersion', and 'seafloor shapes and dip variations'. According to the relation map then, thicker MTD
474 zones may be related to (i) pre-existing depressions in the seafloor (see e.g. Sawyer *et al.*, 2012,
475 Mulder & Alexander, 2001a and Table_Supplementary 1); or (ii) to a local thickening associated with
476 ductile flow of the basal material (shown for sandy flows by Mourgues *et al.*, 2009); or (iii) to thrust-
477 induced elevations of the upper surface. Further analyses on other properties should help limit
478 possible interpretations. As for the 'terminal dispersion' and 'remobilization' nodes, they would
479 cause thinning (rather than thickening), which is not the case here; thus for now, we do not retain
480 them as potential impacting processes.

481 Other descriptors of the Morphology property are not available due to the limited surface area
482 covered by our data. Nevertheless, we note that the *principal direction* descriptor (i.e. principal
483 orientation of the 3D geobody) is impacted by the nodes 'flow direction' and 'topography
484 confinement downwards'. For MTDs A and B, the *principal direction* is NNE, rather than ENE which is
485 the basinward direction. One of the two above mentioned processes could thus have influenced the
486 deposit *principal direction* that eventually became distinct from the main slope dip direction – but

487 these interpretations are uncertain, due to the limited data available for *principal direction*
 488 assessment.

489

490 4.3. Position and Basal Surface (BS)

491 For both MTDs A and B, *lateral erosive walls* only occur along their southern limits, as highlighted on
 492 their basal-surface gradient map (Figure 6). The *lateral erosive walls* descriptor is impacted by nodes
 493 'erosion of underlying material', 'flow direction' and 'existing geomorphology, objects and pathways'
 494 (Bull *et al.*, 2009, Moscardelli & Wood, 2008). These erosive walls are identified on the southern flank
 495 only; they are not aligned with the *principal direction* of the objects. These elements show a probable
 496 impact from node 'existing geomorphology, objects and pathways', which were therefore probably
 497 not symmetric with respect to the main flow direction at the time the event occurred; the 'flow
 498 direction' must have been modified from the ENE (main slope-dipping) direction to a NNE direction,
 499 thereby eroding the neighboring material.

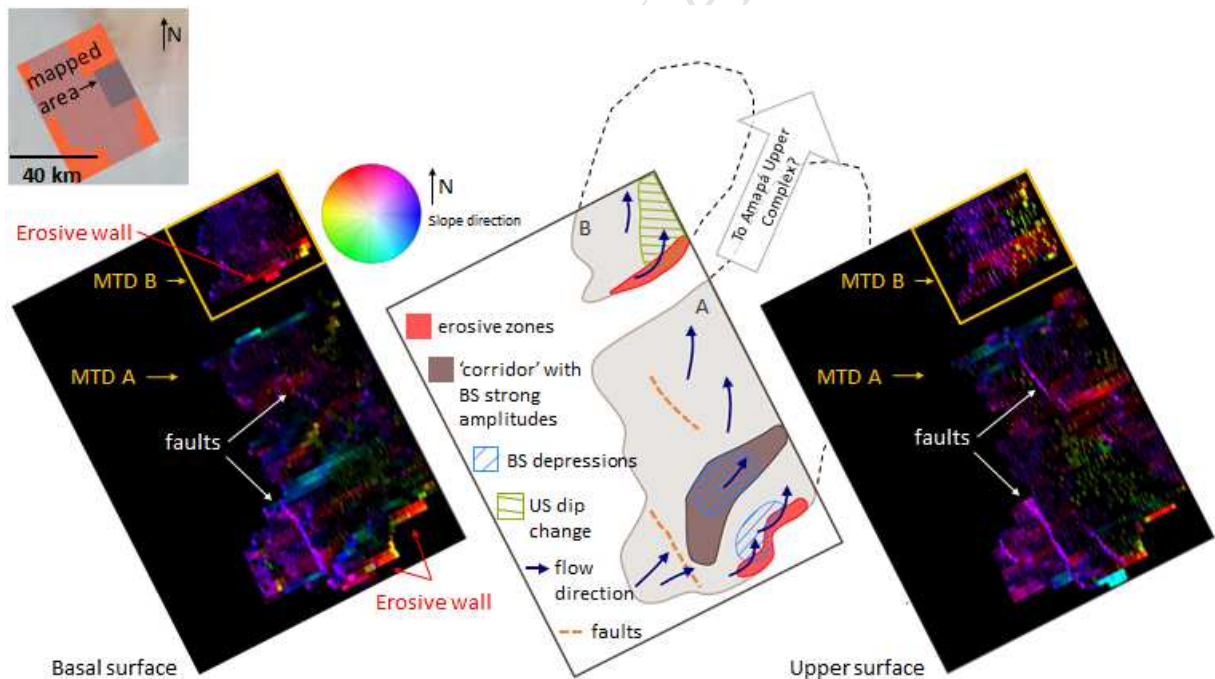


Figure 6. MTDs A and B slope maps of basal surfaces (BS) and upper surfaces (US). Dip direction shown by color hue, dip value by brightness. Both MTDs show a lateral erosive wall in their BS southern regions, and a change in BS and US dip orientation, indicating a change in orientation of the flow. Faults are visible on the BS and US of MTD A. Interpreted map shows a strong amplitude 'corridor' and two topographic depressions of the BS, retrieved from amplitude and topographic maps respectively. Amapá Upper Complex is described by Reis *et al.* 2016 (see Figure 2).

500 MTDs A and B are separated by ~500m laterally and underlined on the seismic sections by a common
501 reflector (basal surface BS), thus implying events occurring in the same time period. The *lateral*
502 *connection to other MTDs* descriptor may be impacted by the node 'remobilization' – suggesting on
503 the one hand that MTD B was made of material remobilized from A –, and node 'existing
504 geomorphology, objects and pathways' – suggesting on the other hand that MTDs A and B result
505 from a single mass movement, whose deposit was separated by a topographic high downslope; note
506 that these possible impacts are contradictory. Now, an *upward connection to other MTDs* is also
507 observed, as the upper part of MTD B is located ~20msTWT above the lower part of MTD A. This
508 *upward connection to other MTDs* node is impacted by the nodes 'triggering cascading mass
509 movements' and 'remobilization' (which, given their spatial relationship, would be from MTD A to
510 MTD B). Process 'remobilization' is enhanced as it appears for the second time. However, based on
511 what was proposed before above (see Figure 6 and comments on the 'lateral erosive walls'), the
512 material of MTD B originates from the WSW and not from MTD A (SE). So, considering the remaining
513 possible processes impacting the *lateral* and *upward connection to other MTDs*, MTDs A and B are
514 probably either signatures of one single event (eventually separated because of pre-existing
515 topography) or cascading events (whose sources were close to each other, failure of MTD A
516 triggering mass movement B).

517 While the basal surface of MTD B has no *BS ramps* and its *slope* is quite regular, from ~-1° to max. [-
518 2.5° to (-5)°], *BS slope* of MTD A varies from [-5.5° to (-11.5)°] upslope, to +1° downslope, and is
519 affected by *ramps* (Figure 7 – see similar examples in Richardson *et al.*, 2011). *BS ramps* are
520 signatures either of node 'triggering cascading mass movements', or of node 'post-deposition
521 regional deformation', or of node 'erosion of underlying material', or yet of node 'existing
522 geomorphology, objects and pathways' suggesting pre-existing ramps on the paleo-seafloor (e.g.
523 Richardson *et al.*, 2011, Mienert, 2009, Frey-Martínez, 2010). Thus, these four processes are more
524 likely to have occurred in MTD A than in MTD B. Further arguments from analyses on other
525 descriptors/properties should favor one among these four.

526 The Basal surface (BS) of MTD A also comprises two deeper zones, or depressions; these account for
527 the previously mentioned variations in thickness. In these depressions, the BS has a *flat sub-*
528 *horizontal* trend. This *BS flat sub-horizontal zone* descriptor may be the signature of a 'plowing effect
529 on underlying material' (Posamentier & Martinsen, 2011, see also section 2.3). This process seems
530 here to be more likely in the two depressions of MTD A. The local variations in thickness analyzed in
531 4.2 can be explained by either (i) pre-existing depression in the seafloor or (ii) local thickening
532 associated with basal ductile flow, rather than thrust-induced elevation of the upper surface (iii).

533 MTDs A and B are both characterized by the descriptor *BS strong amplitude*. Descriptor *BS strong*
534 *amplitude* is impacted by the nodes ‘lithology of underlying material downslope’, ‘fluid overpressure
535 on basal surface’, and ‘plowing effect on underlying material’. In turn, the node ‘lithology of
536 underlying material downslope’ is related to the node ‘lithology of underlying material in source
537 zone’; this indicates that if the medium is homogeneous between the source and deposition regions,
538 then the impedance contrast observed at a *strong-amplitude* basal surface should be explained by a
539 change in the MTDs’ basal material rheology. In MTD A, one current topographic depression shows
540 very high amplitudes, with a negative polarity (Figure 7), whereas in MTD B the polarity of the *BS*
541 *strong-amplitude* region is positive. Based on the relation map then, two scenarios may explain these
542 differences:

- 543 - MTDs A and B have similar acoustic impedances, but their respective underlying material has
544 lower impedance in the south-east (under A) than in the north-west (under C). This could be
545 linked with the occurrence of some degree of fluid overpressure along the BS of MTD A.
- 546 - The underlying material shared by MTDs A and B has uniform acoustic properties, but the
547 material of MTD B results in lower acoustic impedance than that in MTD A. As the material of
548 MTD B probably does not originate from remobilized material from MTD A, the difference
549 would then be due to different transport properties of the mass movement (either of the
550 two ‘branches’ of a single event, or of the two cascading events). For instance, a plowing
551 effect occurring in event A would lead to reorganization of its basal sediments, thereby
552 densifying the bottom of the MTD in one topographic depression (see ‘corridor’ in Figure 6).

553 Here, the relation map enables two possible main interpretations that remain to be ranked
554 depending on further arguments provided by other properties or from posterior contextual
555 information.

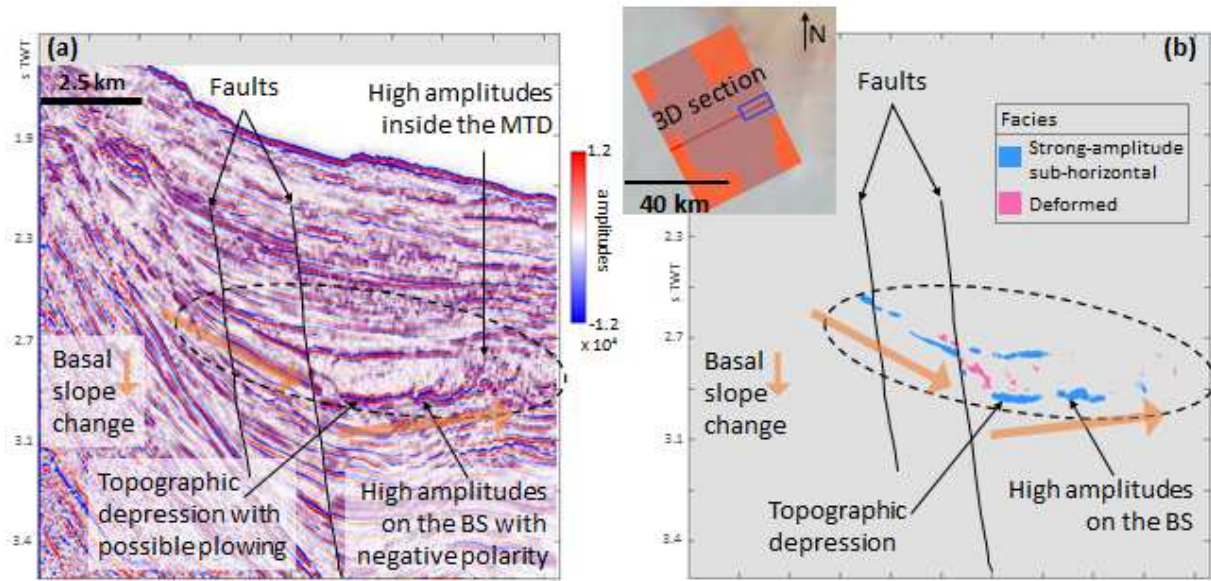


Figure 7. MTD A (dashed circle). Seismic section (a) and seismic facies (b). Faults and topographic depression are highlighted, with possible plowing (*sensu* Posamentier & Martinsen, 2011) on the high-amplitude negative-polarity basal surface (BS) of MTD A. Irregular high amplitudes are also visible inside MTD A. Deformed facies rather appears at the head part of MTD A (similar distribution for C).

556 4.4. Upper Surface (US)

557 On MTD A upper surface (US), *ramps* similar to those as on its BS are visible. According to the relation
 558 map, descriptor *US ramps or ridges* is impacted by the nodes ‘post-deposition regional deformation’,
 559 ‘frontal compression’ and ‘flow direction’ – very different kinds of processes. Here, however, it is
 560 possible to select the most likely: the BS and US *ramps* coinciding on MTD A favor their common
 561 impacting node (‘post-deposition regional deformation’), indicating signatures of a faulting
 562 deformation of the MTD after deposition (Figure 6, Figure 7).

563 The Upper surfaces (US) of MTDs A and B both have a *median slope* gradient of [-1° to -2°]; this
 564 value is much lower than the *median slope* gradient of their basal surface [-3.5° to -7°]. Descriptor
 565 *US median slope* is impacted by the nodes ‘flow behavior: elastic, plastic, fluid’, ‘flow direction’,
 566 ‘topography confinement downwards’, and ‘evaporite deformation and mud volcanism’. A significant
 567 dip change is visible on the US of MTD B (Figure 6)-that may be related to the nodes ‘flow direction’
 568 and ‘topography confinement downwards’; it correlates with the change in the orientation of the
 569 object (see 4.2). In this area, the *US slope* is an additional argument for the occurrence of a change in
 570 flow direction. On the other hand, the ‘flow behavior: elastic, plastic, fluid’ node may explain the
 571 lower *median slope* gradient on the US than on the BS; this is to be compared to the [-1.5° to -3.5°]
 572 *median slope* gradient of two other MTDs of the same cube (MTDs C and D, Figure 3), and to the
 573 current seafloor *slope* of [-1.5° to -3°] in the downslope part. The low *US median slope* of MTDs A
 574 and B thus suggests the occurrence of a rather ‘fluid’ flow, compared to that of other MTDs of the
 575 cube with inferred more ‘viscous’ flows.

576 **4.5. Internal Facies Distributions**

577 As a whole, MTDs A and B are 12% and 11% *chaotic* respectively, with internal variations: both are
578 mostly *chaotic* in their southern part. *Ridged facies* are similarly distributed inside MTDs A and B,
579 with an overall 30% proportion of occurrence for both. Descriptor *chaotic facies distribution* is
580 impacted by the nodes 'flow behavior: elastic, plastic, fluid', 'grains heterogeneity in flowing mass',
581 and 'posterior fluid migrations'; *ridged facies distribution* is impacted by the nodes 'frontal
582 compression', 'flow direction' and 'flow behavior: elastic, plastic, fluid'. These elements show that
583 for both mass movements A and B, when arriving in the northern part, the material probably had a
584 different flow behavior than that in the southern part (consistency of the 'flow behavior' node for
585 both descriptors). A change in compression constraints and flow direction between south and north
586 is also in line with the previously-mentioned orientation change of the objects. According to the
587 other above-mentioned impacting nodes, additional possible interpretations for both MTDs A and B
588 are: increased homogeneity in the acoustic properties of the material in the northern part, and post-
589 deposition uneven fluid migrations occurring inside the southern part of the MTDs.

590 The *deformed facies* proportion of MTD A is quite low, only 2%, whereas for B it is 11%. For both of
591 them, *deformed facies* are seen at the contact between the upslope part of the MTD and their
592 underlying material (Figure 7 (b)); and notably MTD A is 10% *deformed* in its upper part but <5%
593 *deformed* everywhere else. The *deformed facies* descriptor is impacted by the nodes 'flow behavior:
594 elastic, plastic, fluid', 'post-deposition regional deformation', and 'evaporite deformation & mud
595 volcanism'. Thus, for both MTDs A and B (with more quantitative arguments for A), deformation
596 occurred more on the bottom of the head part, either due to a particular flow behavior there, or to
597 post-deposition regional deformation, or to local evaporite- or mud-related deformation in the zone.

598 MTDs A and B have different *transparent facies distributions*: MTD A is only 11% transparent on
599 average, while MTD B is 28% transparent. However, MTD A is >20% transparent inside its two thicker
600 regions; other interior parts of MTD A have unevenly-distributed high amplitudes, roughly aligned
601 with the fractured BS patterns (Figure 7). Descriptor *transparent facies distribution* is impacted by
602 several nodes: 'grains heterogeneity in flowing mass', 'compaction during burial', 'posterior fluid
603 migrations', and 'presence of preserved blocks'. The high-amplitude region inside A (low proportion
604 of *transparent facies*) may correspond to either preserved clasts (of size $\sim 1/3$ of the MTD thickness),
605 or to over-pressured fluids heterogeneously trapped inside the MTD, migrating after its deposition or
606 remaining from an undrained mass transport. Comparatively lower amplitude (transparent) zones in
607 MTDs A and B would then correspond to regions with more internal homogeneity, possibly enhanced
608 by compaction or homogenized fluid drainage during burial.

609 **4.6. Headscarp (HS)**

610 The multiple *headscarps* visible upslope are possibly related to downslope MTDs; however no direct
 611 relationship can be identified between one single MTD (among the five seen in the cube, see Figure
 612 3) and one upslope scarp – preventing us from analyzing descriptor *HS morphology*. Yet these
 613 *headscarps evolve downslope* (Figure 8); this description suggests the impact of two controls: some
 614 large-scale ‘subsidence/uplift, extension/compression’, in the zone (inducing a progradation of
 615 sedimentary structures, as in, for example, Richardson *et al.*, 2011, Ortiz-Karpf *et al.*, 2016, Clark &
 616 Cartwright, 2009), and/or ‘sedimentation rate and type’ (in the sense of a sedimentation increase
 617 with time), according to the relation map. The period of time in which these scarps were created is
 618 from 2.4Ma to present (Gorini *et al.*, 2014, see Figure 8). Knowing the rate of tectonic or isostatic
 619 deformation since 2.4Ma would make it possible to constrain a potential impact on this evolution.
 620 Similarly, as the node ‘sedimentation rate and type’ is itself impacted by the sea-level evolution,
 621 knowing this time more precisely could help confirm or invalidate a eustasy related headscarp series,
 622 and also the above-mentioned MTD *vertical distribution*. The relation map based results do not favor
 623 either of these two interpretations.

624

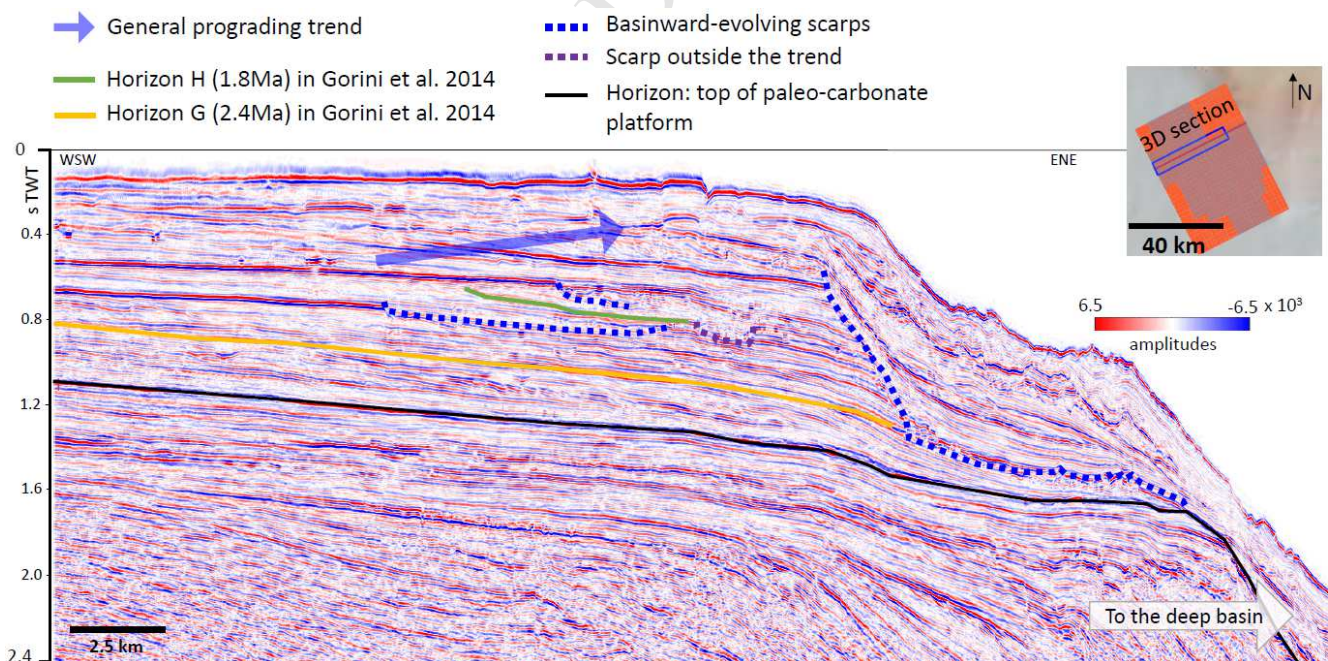


Figure 8. Upslope scarps showing fore-stepping evolution of the erosion on one dip seismic section from our seismic cube.

625

4.7. Summary of all results retrieved through the relation map analysis

The material of MTDs A and B probably originates from the WSW (rather than from the south), and both MTDs are probably signatures of a single event, or cascading events (one mass movement triggered by the change in slope stability induced by the other mass movement). MTD A is more likely to have been subject to post-deposition regional deformation, in the form of extensional faults, than MTD B.

Both MTDs may have resulted from more fluid-like material flows than the other MTDs of the same cube. A plowing effect may have occurred during mass movement A, more likely located in one of the two observed topographic basal depressions; furthermore, right above the deepest part of these depressions, the acoustic properties of MTD A are relatively homogeneous. Preserved clasts or trapped/undrained fluids may be found in other parts of its southern region. Deformation occurred more in the bottom head part of MTDs A and B, due to either a more viscous-like basal flow, or to post-deposition deformations.

For MTDs A and B, the flow direction during the event was modified in its distal part. The flow behavior of their material probably differed in the southern parts of both MTDs from that in their respective northern parts. In particular, compression and/or post-deposition uneven fluid migrations may have impacted the southern part of MTD A – compression is more obviously related with a change in orientation, corresponding to a topographic impact. In their northern parts, a greater homogeneity in MTDs acoustic properties is found, suggesting more homogeneous distribution of material properties at the time of deposition, and/or homogenization by posterior compaction effects or homogenized fluid drainage (during burial).

Two possible processes may explain the difference in polarity between the basal surfaces of MTDs A and B (in places where the basal surface has strong amplitude): either a lower impedance of the underlying material in the south (possibly including some fluid overpressure on the contact surface); or the two 'branches' of a single event (or the two cascading events) with different transport properties, e.g. a possible plowing effect in mass movement A densified its bottom sediments during deposition.

Concerning more general aspects, the three main stages of the "MTD layers" in the stratigraphy may be signatures of eustatic cycles – if other alternating systems like channel-levee systems are detected in the sedimentary pile, which is uncertain in our data. Some regional deformation due to tectonics or isostatic movements, inducing global progradation and/or sedimentation rate increase, may have

657 occurred during the whole period when the 5 MTDs were deposited. And finally, the southern part of
658 the cube was less exposed to mass-transport deposition during this period.

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660 5. Assessing the validity of results

661 In this section, we analyze the correlation between results based on our proposed relation map and
662 previous published studies on the Amazon Basin.

663 5.1. To what extent are our results consistent with previous knowledge on the Amazon 664 Basin?

665 Our seismic dataset is located in a very proximal region of the Offshore Amazon Basin (~120 to 1500
666 m deep), close to the upslope domain of the Amazon deep-sea fan. This region corresponds to the
667 junction between the current shelf break, the Amazon deep-sea fan and the area affected by the
668 Amapá Megaslides Complex (Figure 2). In the present study, we analyzed cube-scale MTDs (a few
669 tens of km). Previous studies of the northern part of the basin focused on much larger, basin-scale
670 MTDs (a few hundreds of km), observed on 2D seismic data. In their studies, Gorini *et al.* (2014), Reis
671 *et al.* (2016) and Silva *et al.* (2016) propose an age spanning from late Miocene to late Pleistocene for
672 different MTDs of the Amapá Upper Complex. These basin-scale MTDs typically originated from
673 marine slope instabilities. Maslin *et al.* (2005) focused on Quaternary MTDs of the 'Western Debris
674 Flows' complex, considered as typical MTDs induced by the development of the deep-sea fan (Figure
675 2). These two kinds of MTDs characterize the entire basin sedimentation.

676 Thus, the MTDs characterized in this paper are at a much smaller scale than those previously studied
677 across this basin. Nevertheless, our results show the consistency between the results of the analysis
678 based on the relation-map and the known context of the Amazon Basin.

679 First, we know that MTDs in the northern Amazon Basin region, resulting from mass movements
680 dated from the late Miocene to Present, are mostly debris flow signatures. General classifications
681 define debris flows as being composed of a matrix containing internal blocks (Nelson *et al.*, 2011),
682 resulting from 'spreading' (*sensu* Mourgues & Cobbold, 2006) or from 'mixed plastic-fluid' flow
683 (*sensu* Posamentier & Martinsen, 2011), that still retains some competence and not being as
684 energetic as a turbidity current (Lee *et al.*, 2007).

685 The MTDs we studied are at most a few Ma old, corresponding to the same period of deposition as
686 the Amapá Upper Complex (Reis *et al.*, 2016) and the superficial MTDs described in the literature
687 (e.g. Damuth & Embley, 1981, Damuth *et al.*, 1988, Maslin *et al.*, 2005). A few elements on MTDs A
688 and B are in line with the interpretation of a debris flow type: (i) homogeneous acoustic properties
689 (with low impedance contrast), alternating with heterogeneous regions where either clasts or fluids
690 may be trapped. (ii) The overall limited presence of deformed facies reveals a very limited plastic

691 deformation, which is characteristic of material flows rather than of slides or creeps (Posamentier &
692 Martinsen, 2011) in which deformation plays an important role. (iii) Erosion signatures can be
693 generated by debris flows, although slides can also erode their underlying material. Here, the erosion
694 marker is located at a change in the direction of the material displacement, and some compression
695 has left marks inside the MTDs; this tends to favor debris flow behavior rather than slide behavior.

696 Second, we know that the entire Amazon Basin is subject to ‘gravity-tectonic’ deformation (Reis *et*
697 *al.*, 2016), which produces extension in its proximal part, and distal compression. The faults observed
698 on MTD A could be a sign of the proximal extensional constraints – although they are possibly also
699 linked to surficial compaction. Why they are not visible on MTD B is either linked to the (slightly)
700 more distal position of MTD B (4-6 km more distal), or to the position of A closer (~10 km) to the
701 edge of the deep-sea fan – generalized faulting in the southern part of the seismic cube seems to
702 favor this argument. This leads us to the third point.

703 Third, results based on our relation map on MTDs A and B seem to be consistent with the presence of
704 the deep-sea fan just south-east of the studied seismic cube (Figure 2). It has been shown that this
705 deep-sea fan has created three major kinds of influences since its onset in the Middle-Late Miocene
706 (Figueiredo *et al.*, 2009; 9.5 – 8.3 Ma according to Gorini *et al.*, 2014): acting as a secondary source of
707 sediments for transport into the deep basin (e.g. Reis *et al.*, 2010, Maslin *et al.*, 2005, Araújo *et al.*,
708 2009), having topographic control over the seafloor shape, and structural control (Watts *et al.*, 2009)
709 by flexuring the margin under its weight.

710 In our study, MTDs A and B are shown to originate from the paleo-shelf break; yet their direct
711 environment may have been impacted by the presence of sediments coming from the fan direction,
712 as suggested by the difference in BS polarity between MTDs A and B that were deposited either
713 simultaneously or within a short period of time. Over such a short distance between the two MTDs, a
714 local process (such as the presence of fluid, or locally different material properties) probably explains
715 this inversed polarity. Post-deposition compaction, and/or fluid migrations preventing efficient
716 drainage from the BS of MTD A, could explain this difference, e.g. in the case of fluid present under
717 MTD A (hypothesis that would be supported by the presence of fluids *inside* A too). Alternatively,
718 near-fan sedimentation may be subject to different deposition conditions; these may include
719 different sediment inputs, transported via contouritic currents around the fan or turbiditic currents
720 originating from the fan that, mixed with recently deposited sediments downslope, would eventually
721 yield lower-impedance sediments. This hypothesis is supported by the BS polarities of other MTDs of
722 the cube, which are always negative in the southern region (close to the fan) and positive in the
723 north – assuming the influence of the fan has remained similar since the deposition of MTDs A and B.

724 The topographic control is highlighted in our results via the change in flow direction in MTDs A and B,
725 which may be evidence for a topographic constraint. The deep-sea fan itself is an accumulation of
726 material that creates a NW-dipping slope in the seafloor, already present at the time of deposition of
727 MTDs A and B. The debris flows probably changed their main direction from dip-oriented (originating
728 from the WSW) to more northward-oriented, i.e. following the main slope direction in the more
729 distal region of the cube, impacted by the fan sediments. Topographic control is also consistent with
730 the fact that the southern part of this sub-basin, where the fan represents a topographic high, was
731 less exposed to mass-transport deposition.

732 The structural control results from the weight of the Amazon deep-sea fan itself. The flexure caused
733 by the fan load has greatly impacted the basin subsidence since the Late Miocene - Pliocene (Watts
734 *et al.*, 2009). Here the distance between MTDs A and B is only ~10km. Nevertheless, we suggest that
735 the presence of faults only in MTD A and not in MTD B may be related to the increased deformation
736 near the upper domain of the fan compared to other places in equivalently proximal regions, which
737 are all subject to basin-scale extensional constraints. This hypothesis is supported by the position of
738 the seismic cube at the junction of three domains (shelf, fan and basin) and within a strongly flexured
739 zone (Watts *et al.*, 2009, see Figure_Supplementary 2 in supplementary material). Moreover, the
740 processes that might have impacted the basinward-evolving headscarps upslope, may involve partly
741 this fan control, and partly the larger-scale gravity-tectonic deformation of the entire basin.

742 Finally, the Amazon River sediment discharge has kept increasing since its onset as a transcontinental
743 river (Gorini *et al.*, 2014). This element is recovered by the basinward evolution of upslope
744 headscarps (see section 4.6).

745 **5.2. How do our new unexpected results compare with previous literature on the Amazon** 746 **region?**

747 According to our results, MTDs A and B were affected by deformation in the bottom of their head
748 parts. Outside the MTDs, the deformed facies otherwise characterizes slope-deformed facies.
749 Deformation within the heads of the MTDs is caused by either specific flow behavior or by post-
750 deposition deformation or evaporite/mud-related deformation in the zone, which highlights the
751 deposition process: MTDs onlapping the continental slope and subject to internal, very small-scale
752 post-depositional gravity-induced deformation – or to syn-depositional viscous ‘attachment’ (see
753 Moscardelli & Wood, 2008 for ‘attached mass transport complexes’, whose upper part shows a
754 deformed, slump character). In 2D-based studies, scale / resolution effects may prevent 2D data from
755 revealing such detailed variation in deformation. Note that the scale argument also tends to exclude

756 the impact of deformation by any tectonic- or non-tectonic process, which, given the small size of our
757 MTDs, would probably rather affect the whole geobodies.

758 We have shown that our MTDs originate from upslope paleo-scarps. Former studies on the Amazon
759 Basin revealed MTDs whose headscarps are even more distally located than the area covered by our
760 cube. These larger, more distal MTDs have been interpreted as originating from the submarine slope
761 (Reis *et al.*, 2016). The relationship between these two sets of MTDs has not yet been established.
762 However, the north-northeast (NNE) principal direction of MTDs A and B suggests a link with the
763 MTDs of the Amapá Upper Complex (Figure 6).

764 Our results suggest small-scale variations inside MTDs A and B. For example, MTD A includes regions,
765 among which some have been homogenized since their deposit, and others have been subject to the
766 presence of fluids, clasts, or apparent heterogeneity. Assessing the relevance of these internal
767 variations is difficult when comparing to MTDs observed at basin-scale, for which no conclusion can
768 be drawn at our finer scale. However, the frequent reworking of the recent sedimentary pile due to
769 the influence of the fan or to the high sedimentary influx (Reis *et al.*, 2010, Reis *et al.*, 2016) supports
770 these observations.

771 MTD A is not visible on any available 2D seismic line. MTD B can be found on one line, on which its
772 extent is highly uncertain (Figure 9). Our results should thus be understood as concerning only parts
773 (the head parts) of potentially larger MTDs (although probably not as large as the basin-scale ones).

774 Global analysis of the five MTDs in our cube suggested a signature of eustatic cycles in the vertical
775 regularity of “MTD layering”, as long as this regularity is also visible in the interbedded sediments –
776 which was not the case, making this suggestion highly uncertain. These “MTD layers” do not have the
777 same properties (number of objects, degree of internal heterogeneity, direct above- and below-
778 environment), so that ‘cycles’ are difficult to depict. Moreover, the average thickness of MTDs
779 decreases from the deepest to the shallowest, i.e. it decreases with time. This is not in line with the
780 above-mentioned increase in sediment discharge from the Amazon River; what is more, the increase
781 is not recovered in the regular spacing between the three “MTD layers” indicated in Figure 4. Thus,
782 no conclusion can be drawn on this potential eustatic influence. The limited content of the relation
783 map is not yet sufficient to explain this decreasing thickness trend.

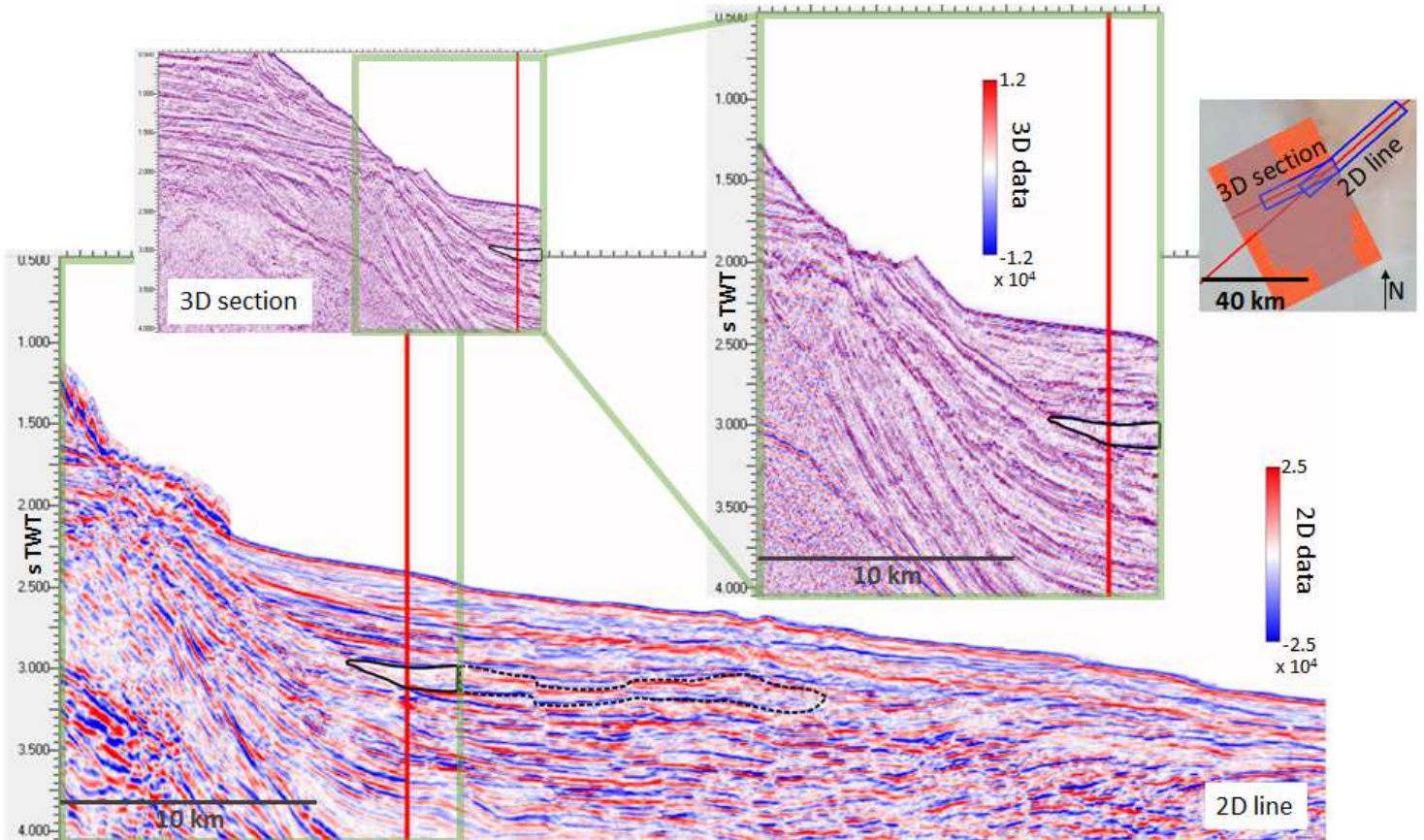


Figure 9. MTD B illustrated on a 2D seismic line. Solid black line: contour of MTD B drawn on a section extracted from the 3D cube (projected onto the 2D line). Dashed line: possible continuation of MTD B, interpreted from the 2D data.

784

785 Considering sections 5.1 in which our results agree with the general context of the region, and 5.2, in
 786 which most of unexpected results refer to the scale or availability of data, we propose to validate our
 787 new methodology. In section 6, we discuss its main limits and potential outlooks.

788

789 6. Discussion

790

791 6.1. Sensitivity analysis

792 In the graph analyses, some processes are inferred only once from a descriptor; if the descriptor is
793 not available, the process will not be hypothesized at all. Conversely, other processes are suggested
794 by several different descriptors, which reduces their uncertainty. Lastly, some processes are
795 suggested by some descriptors but contradicted by others. In this case, the hypothesis is rejected and
796 the process is not inferred. All these analyses may differ if insufficient data content / quality prevents
797 reliable property descriptions. Here, we assess the loss of results from our methodology for
798 situations with deficient data, leading to one or several missing descriptors.

799 (i) Let us first consider the case where the thickness/resolution ratio is less than 3 (see
800 Table_Supplementary 2). This could happen for occurrences of thin MTDs in a poorly-resolved
801 seismic dataset. This typically limits the acquisition of Internal Facies Distribution descriptors to
802 studies on rather shallow MTDs. If these descriptors were lacking in our application, this would
803 reduce our confidence in several processes: the heterogeneous fluid migrations, the south-north
804 difference of flow behavior within the MTDs and their direction change. It would also suppress
805 hypotheses concerning preserved clasts and the different compaction/drainage processes inside
806 the objects. Thus, this situation removes information on rather fine-scale transport properties
807 and post-depositional processes, which may be crucial, for example, in the context of
808 exploration.

809 (ii) In another case, the picking grid of surfaces (basal and upper surfaces of the MTD, headscarp)
810 may be too low to obtain descriptors depicting the surfaces' morphologies: ramps or ridges,
811 median slope values, presence of specific indicators like plunging pool / terracing and erosional
812 descriptors on the basal surface. In our application, such a loss reduces our confidence in the
813 proposed direction change (absence of the asymmetric erosive walls and of the US dip change in
814 MTD B), and in the relatively 'fluid' behavior of the MTDs; it also cancels the hypothesis
815 concerning post-depositional regional deformation (faults). In our case, then, only a few
816 hypotheses would be less supported, and the post-depositional deformation could be easily
817 guessed from global observation of the seismic data. In other cases however, the absence of
818 'basal ramps' and 'multi-terracing downslope' may prevent the retrieval of the 'cascading
819 events' hypothesis for example, which could lead to mis-interpretations.

- 820 (iii) Another possible situation is that the seismic amplitude range is not appropriate or sufficiently
821 reliable to distinguish between 'strong' and 'normal' reflectors (due to acquisition or processing
822 uncertainties), in which case, part of the internal facies descriptors may be lacking ('transparent
823 facies distribution', 'presence of preserved blocks') as well as the 'basal surface strong
824 amplitude' descriptor. In our application, fluid migrations, different compaction/drainage, as
825 well as differences in lithologies, would not be proposed at all. This supports the general need
826 for good-quality amplitudes to assess the presence of fluid.
- 827 (iv) Finally, data coverage may limit the acquisition of several descriptors, particularly within the
828 Morphology, Position and Global Environment properties, and also including the Headscarp
829 descriptors and toe-related descriptors if these regions are outside the dataset. From our
830 application, a few hypotheses would then be missing: a potential link between MTDs A and B,
831 arguments concerning remobilization from A to B, and impact of large-scale deformations or
832 sea-level cycles on the sedimentation in the zone. Such descriptors therefore yield crucial
833 information on the basin- or regional-scale controls, as well as potential genetic relationships
834 between MTDs, that may make it possible to classify them in series, or as signatures of regional
835 events (e.g. attached MTDs). Conversely, in our study, having access to the toe region of the
836 MTDs would have provided more indications on the paleo-seafloor topography and existing
837 geomorphology at the time of the mass movement, as well as the flow behavior; it would also
838 have enabled more reliable comparisons of volume and all morphological properties, yielding
839 more constraints on the transport processes and more reliable comparisons between objects.

840 It is unusual that all the above mentioned data deficiencies occur simultaneously. Generally, to be
841 identified in seismic data, an MTD has a sufficient thickness to define its basal and upper surfaces.
842 Large MTDs are often not completely imaged by 3D seismic data with relatively good resolution,
843 leading to either missing head or toe region; they may otherwise be studied using 2D seismic data
844 with lower resolution but including the entire extent of the object.

845 Missing parts of the object will generally hide information on regional processes, whereas an
846 entirely-imaged MTD in a poorly-resolved dataset will hide information on finer-scale transport style,
847 posterior internal modifications and on the current state of the MTD. Too-loose picking of MTD-
848 related surfaces leads to missing transport erosional properties and hence critical information on the
849 flow direction and on the state of the paleo-seafloor, as well as posterior impacts of fluid migrations
850 or large-scale deformations. However, depending on the application, interpreters use data that
851 correspond to their needs. For reservoir-scale studies, high-resolution seismic data are preferred,
852 while for assessing large-scale controls, datasets with larger coverage may be chosen at the expense
853 of a lower resolution. Studies implying fluids will require precise surface definitions and a high degree

854 of confidence in the distribution of the seismic amplitudes. Thus, despite the lower confidence with
855 fewer available descriptors, the graph-based methodology can also be used in applications with
856 limited data.

857 **6.2. What is the uncertainty related to our methodology?**

858 The limited amount of data and limited information in the relation map reveal that the results
859 produced by our methodology are subject to three main kinds of uncertainty.

860 The first kind of uncertainty is related to the input data. The seismic acquisition and processing
861 stages, the interpretation of surfaces, the resolution and the coverage of the dataset are the key
862 elements introducing uncertainty in the inputs (see preceding section). Like in any seismic
863 interpretation, depth-converted data might also add some uncertainty, e.g. velocity pull-up/push-
864 down effects that affect both surface and global descriptors. Additionally, the facies classification
865 (Internal Facies descriptors) itself involves some uncertainty, although the labels given to groups of
866 'transparent facies', 'chaotic facies', etc., are normally checked on several seismic sections; two
867 different geological facies may produce the same response in terms of seismic facies (e.g. Sun *et al.*
868 (2017) show disrupted, low-amplitude patterns due to gas chimneys that might be considered
869 'deformed' or 'chaotic' facies). However, the descriptors used here are supported by seismic
870 interpreters' experience. It should also be noted that initially flat morphologies and surfaces may be
871 bent or steepened by large-scale deformation processes; this could be included in the graph (e.g. by
872 adding an edge between nodes 'post-deposition regional deformation' and 'BS median slope') if
873 other parts of the graph are adapted accordingly (e.g. analyzing facies distributions and surface
874 properties along a dipping direction). For now such considerations are not included, which might
875 limit the graph to cases with little, or known, steepening of this kind.

876 A second kind of uncertainty is related to the relationships, or laws, comprised in the relation map.
877 These laws come from the literature, but they also have limits; a possible, quantitative way to take
878 these limits into account would be to weight every edge of the graph, thereby weighting the
879 confidence of each possible interpreted physical process during the interpretation procedure.

880 The final kind of uncertainty is related to the construction of the relation map. The contents of the
881 two lists in Table 1 and Table 2 were chosen based on a bibliographical study, which is the source of
882 two main biases:

- 883 • The number of published studies, and the number of studies we used, are limited, which
884 necessarily limits the physical processes and MTD descriptors encountered in our study.
885 However, we used a variety of sources, to ensure the studies came from several different

886 backgrounds (numerical, conceptual or analog modeling / seismic interpretation) and are as
887 little as possible affected by this bias.

888 • Depending on what can be modelled and what cannot, the literature itself is biased. For
889 example, among the links between Table 2 and Table 1, there is no direct link between
890 trigger type and final MTD properties, because the physics that describe a trigger differ from
891 the physics that describe a fall/flow, and to date, no study has tackled this link.

892 The selection of the most relevant elements to build our two lists was an iterative process. A few
893 properties that are described in the literature were intentionally not included in this study; in
894 particular, fine-scale properties of a wasted material, e.g. its grain size distribution or grains friction
895 coefficients. Such properties certainly impact the mass movement, and possibly the MTD itself (e.g.
896 when a front of larger grains generates 'tongues' at the toe of the MTD, as suggested in Pouliquen *et*
897 *al.*, 1997). Yet we considered them as 'side' effects compared to others, especially since in several,
898 the internal lithology of the MTD must be known, which is not the case in our seismic analysis. Too
899 large-scale, or too rare, processes, such as the displacement of water that creates a propagating sea
900 wave and may trigger other instabilities in another region of the basin, were also disregarded in our
901 analyses. Finally, it should be noted that all the elements listed in Table 2 depend on a timescale;
902 they should always be considered as long- or short-term *relative* to some other phenomenon.

903 In order to quantitatively assess this last kind of uncertainty, ideally the relation map should be
904 further developed, to include all the relationships left out of this work, until an entire formal
905 ontology has been created with quantitative confidence weighting on edges according to how often
906 they are cited and/or demonstrated in the literature. This would be the ideal solution, probably very
907 complex to reach.

908 This possibly high uncertainty (depending on the three factors mentioned above) is in line with the
909 present approach of suggesting several scenarios, one of which will finally be chosen by the
910 interpreter using other sources of information (geological context, other kinds of data such as log
911 data that noticeably increases confidence in facies interpretations). Our approach does not make it
912 possible to select one scenario with certainty, but rather offers several possibilities. It is an attempt
913 to reveal an on-going interpretation procedure when only a few input data and published results are
914 available. The interpreter then uses the results of the relation map as he/she needs them, and
915 consequently remains the sole decision-maker.

916 **6.3. Future outlook, other developments and uses of our methodology.**

917 The graph constitutes a knowledge base using only information from the literature. The idea behind
918 it is to convey the scientifically accepted information that already exists (within the existing nodes
919 and edges), to be used jointly with specific information concerning a case study for applications.
920 Improvements to the results may come from both sides (graph content and data quality).
921 Improvements to the methodology will come from the use of the graph itself.

922 The first possible extension is obviously its automation through a dedicated numerical
923 representation: the GraphML language, as promoted by e.g. Schauburger *et al.* (2016), and the Web
924 Ontology Language (OWL)³, as promoted by Malik *et al.* (2010) and implemented for ontology edition
925 by Musen (2015). Many details are provided in the present paper on the steps of interpretation,
926 descriptor by descriptor, node by node; but in a numerical framework, these results could be
927 obtained automatically, which would considerably accelerate the process. With this view, using
928 quantitative weights on edges, as suggested above, would certainly benefit the procedure itself, and
929 would yield some quantitative uncertainty information. Automated acquisition of the MTD
930 descriptors may be hard to implement, but this point can be solved separately and does not
931 jeopardize the graph-based method itself.

932 Our work can be further extrapolated by using the relation map in a different way thanks to its
933 automated (i.e. rapid) version. An interesting application would be to test several hypotheses on
934 unknown values of certain MTD descriptors. The resulting hypothetical interpretations, if different,
935 could be compared with outside knowledge about the MTD, thus enabling selection of the most-
936 likely value of the descriptors of interest. Trials could then be run to see whether, based on a partial
937 MTD characterization (i.e. having only part of MTD descriptors' values), using the relation map would
938 make it possible to infer the values of the others. Another approach would be to input some "a-priori
939 bias" on the edges' weights, based on external information. The results of the modified-graph would
940 then take this information (e.g. contextual knowledge) into account.

941

³ Developed by the W3 Consortium on Semantic Web: <https://www.w3.org/OWL/>, last accessed Sept. 2018

942 7. Conclusion

943 We propose the use of an ontology for MTD interpretation in seismic data based on the combination
944 of literature sources. To this end, we built a knowledge base from existing literature in the form of a
945 graph (relation map). A graph-based methodology is provided to infer potential causal processes for
946 the seismic signatures of MTDs. This novel method was applied on a case study with a 3D seismic
947 dataset from the Amazon Basin, which validated the methodology.

948 Our methodology yields objective proposals for interpretation based only on the ontology and the
949 input data, with no other prior information. Some uncertainties linked to the relation map itself and
950 to the input data remain. In a more complete interpretation process, additional information may
951 make it possible to select the most-likely interpretation among those proposed by our method.

952 Improvements in the relation map will enable quantification of the probability of each interpretation
953 proposed. Our work is a first step towards a more complete ontology, which we believe will help
954 share new knowledge for various uses of MTD interpretation.

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964 of this article.

965 9. Supplementary material

966 Here we give the full list of edges of the knowledge-based graph (relation map)
967 (Table_Supplementary 1). The reference column provides non-exhaustive examples of previous
968 studies whose results support the corresponding edges. Studies by Lafuerza *et al.* (2009), Lacoste *et*
969 *al.* (2012), Frey-Martínez *et al.* (2011), Goujon *et al.* (2007), Chemenda *et al.* (2009), Elverhoi *et al.*
970 (2010), Laberg *et al.* (2017), Li *et al.* (2017), Ogiesoba & Hammes (2012), and the Geological Survey of

971 Norway website (<https://www.ngu.no>, last accessed in January, 2018) were also used as
 972 contributions to our knowledge base, although they are not mentioned in the text of this article.

Table_Supplementary 1. Edges of the graph. Columns indicate the source node and target node, the directed/undirected character of the edge, and reference(s) that support its definition. The second tab in the table gives all the references used in the first tab. The third tab gives all the edges connected to MTD descriptors nodes.

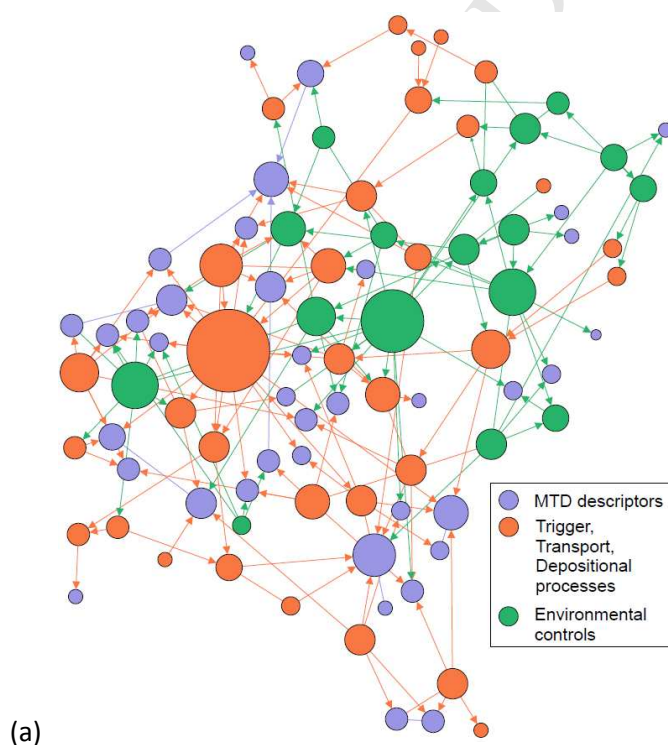
(Attached in a separate file.)

973 Table_Supplementary 2 provides details on the limits of detection for the MTD descriptors listed in
 974 Table 1.

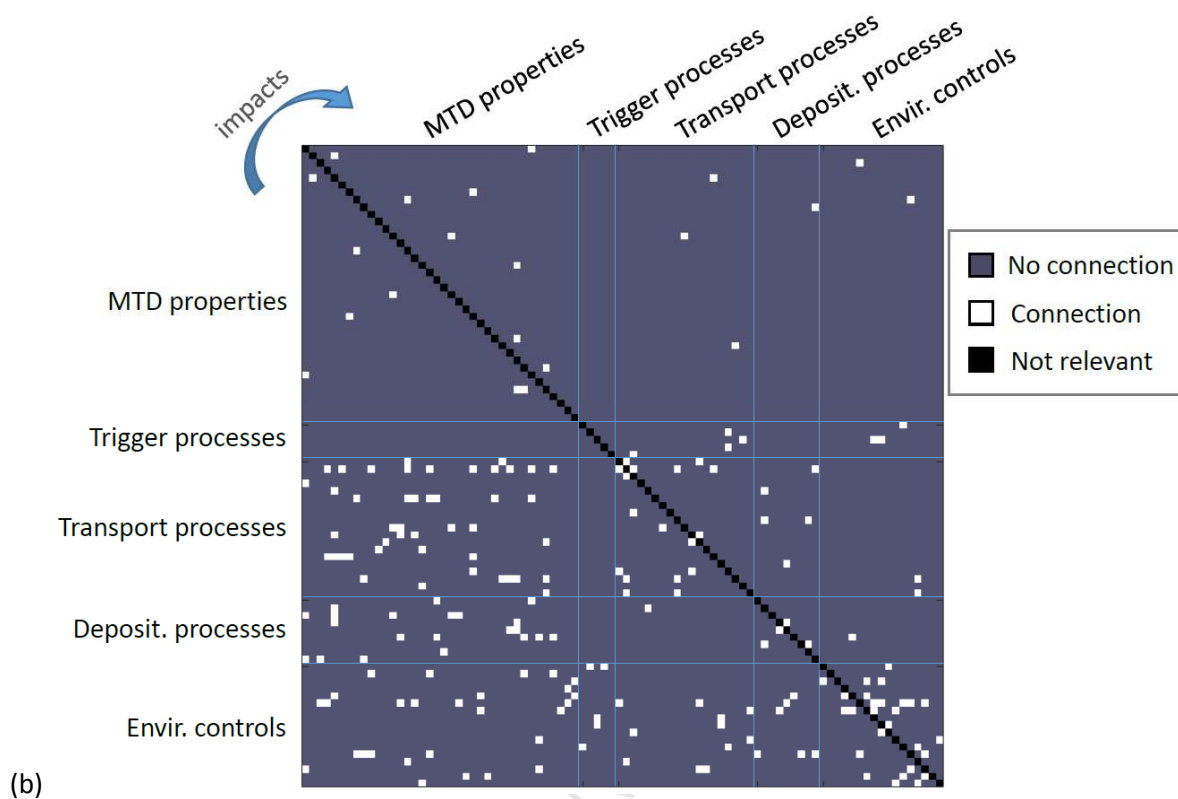
975 *Table_Supplementary 2. Detection limit for descriptors of Table 1, in terms of dataset coverage, resolution, and other
 976 aspects.*

977 **(Attached in a separate file.)**

978 We also provide a figure illustrating one possible visualization of the graph (Figure_Supplementary 1
 979 (a)) and the adjacency matrix of the graph (Figure_Supplementary 1 (b)). The visualization highlights
 980 the variation in 'degree' between nodes (represented by the size of the node), indicating which
 981 nodes have the highest number of connecting nodes. The adjacency matrix shows the links between
 982 nodes directly in a less graphical way; with this matrix, we show that no direct impact has yet been
 983 proven in the literature between trigger processes and MTD descriptors. These representations were
 984 obtained using the Gephi software (<https://gephi.org/>).



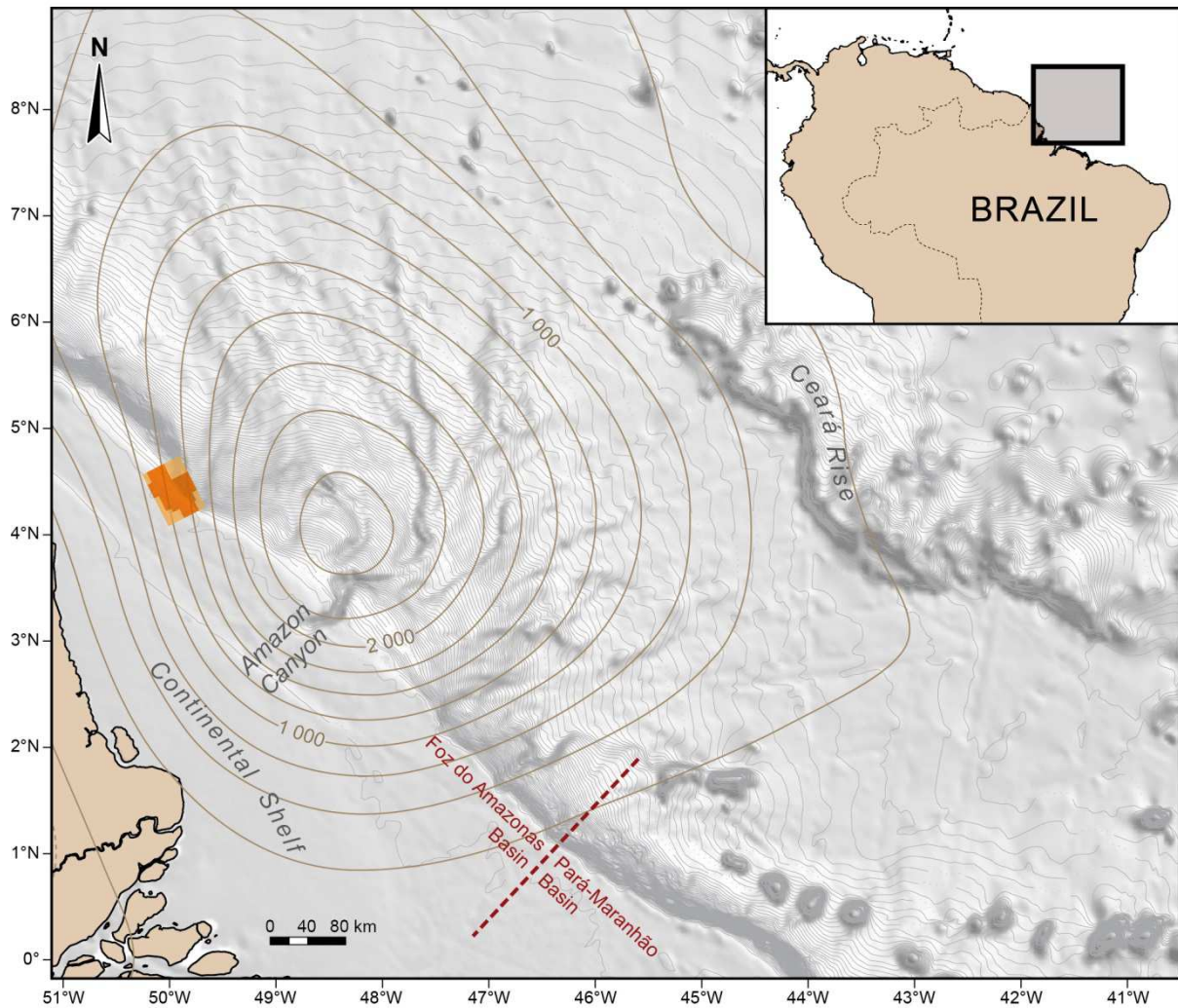
Figure_Supplementary 1. Knowledge-based graph representations: (a) one possible visualization, and (b) adjacency matrix. Figures obtained using the Gephi software (<https://gephi.org/>).



(Figure_Supplementary 1 - continued)

985

986 Finally, we include a bathymetric map by Watts et al., 2009 (Figure_Supplementary 2), showing
 987 results of their calculation of flexure due to the fan load. The position of the seismic cube used in the
 988 present study has been added, to demonstrate its critical position and potential variations in fan-
 989 induced flexure inside the cube.



Figure_Supplementary 2. Bathymetric map of the Offshore Amazon Basin showing the impact of flexure caused by the fan load; from Watts et al., 2009 and Rodger, 2009. Solid lines show the flexural depression (contour interval: 250 m). The inland flexural bulge is not visible on this map. The 3D seismic cube is mapped with available seismic data in dark orange.

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Sizes (desired width) and colors of Figures and Tables

Figure 1. 2 columns if (a) and (b) are stacked horizontally, 1 column otherwise. Color needed.

Figure 2. 1.5 columns. Color needed.

Figure 3. 2 columns. Color needed.

Figure 4. 1.5 columns. Color needed.

Figure 5. 2 columns. Color needed.

Figure 6. 1.5 to 2 columns. Color needed.

Figure 7. 1 column (or 2 columns, (a) and (b) stacked horizontally). Color needed.

Figure 8. 2 columns. Color needed.

Figure 9. 2 columns. Color needed.

Table 1. 2 columns. No need for color.

Table 2. 2 columns. No need for color.

Table_Supplementary 1, Table_Supplementary 2, Figure_Supplementary 1 and Figure_Supplementary 2 are supplementary material.

Descriptors	Properties
thickness variation average thickness width variation horizontal aspect ratio volume surface area maximum horizontal length principal direction presence of 'tongues' at toe	Morphology
BS median slope BS flat sub-horizontal zone plunging pool indicator multiple terracing downslope BS ramps scours, grooves or striations lateral erosive walls BS strong amplitude	Basal surface
US median slope US ramps or ridges US with turbidites on top	Upper surface
upward connection to other MTDs lateral connection to other MTDs near structural elements laterally runout distance	Position
HS downslope evolution HS morphology	Headscarp
presence of preserved blocks preserved blocks size chaotic facies distribution transparent facies distribution faulty facies distribution ridged facies distribution thrust fault angle increase to toe lithology distribution in MTD deformed facies distribution	Internal facies distributions
MTD proportion in sedimentary pile lateral distribution of MTDs vertical distribution of MTDs	Global environment

gravity, short term
 seismicity, short term
 fluid overpressure, short term
 offshore events and waves
 chemical effects
 flow velocity and energy
 flow behavior: elastic, plastic, fluid
 local fluidization
 local thickening of flowing material
 volume of transported material
 flow direction
 modifying basin morphology
 inducing seismicity
 triggering turbidity current
 triggering cascading mass movements
 erosion of underlying material
 plunging pool effect
 plowing effect on underlying material
 detached MTD
 grains heterogeneity in flowing mass
 fluid overpressure on basal surface
 fluid overpressure in moving mass
 initial potential energy of mass
 lithology in transported mass
 frontal compression
 loss of mass
 remobilization
 compaction during burial
 posterior fluid migrations
 post deposition regional deformation
 trigger turbidity current at stop
 post deposition of turbidites
 terminal dispersion
 seismicity or waves, long term
 evaporite deformation & mud volcanism
 sea level evolution
 basin depocenter position
 subsidence/uplift, extension/compression
 existing geomorphology, objects and pathways
 sedimentation rate and type
 pore pressure increase by compression
 pore pressure increase by fluid migration
 permeability increase
 lithology of underlying material in source zone
 initial aspect ratio and top of mass slope angle
 topography confinement downwards
 seafloor effective friction angle
 seafloor shapes and dip variations
 source domain in basin
 lithology of underlying material downslope

Trigger phase	Mass movement properties
Transport phase	
(Post-) deposition phase	
Environmental controls	